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THE DESIGN AND IMPLEMENTATION
OF A POSITION MEASURING SYSTEM FOR
A REMOTELY CONTROLLED VIDEO CAMERA

by

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The Design and Implementation of a Position Measuring System for a Remotely Controlled Video Camera

by

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Captain, United States Marine Corps
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Submitted in partial fulfillment of the
requirements for the degree of

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June 1989

ABSTRACT

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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I. INTRODUCTION

A. BACKGROUND

The old saying that "every solution breeds new problems", while somewhat pessimistic, quite often rings true in today's increasingly technical world. One such example is the use of infrared (IR) sensors for the detection, tracking and/or identification of targets in a combat environment. IR sensors are ideally suited for use on today's battlefield. They are passive, i.e., they do not need to emit energy in order to detect the presence of potential targets. This allows them to operate during times of emission control when many other target detection systems are useless. They have the ability to "see through" many forms of camouflage and concealment, dust, clouds, smoke, etc., that might otherwise afford an enemy target a safe haven. Additionally, because almost everything on today's battlefield generates some degree of infrared energy, IR sensors can be used to locate and identify a wide variety of targets.

The extent to which a particular IR sensor is useful depends primarily on its ability to detect and identify targets reliably and accurately. Detection of the target is primarily a function of the IR sensor's sensitivity. The classification of a received IR signal as a potential target or as background noise, while still dependant on the sensitivity of the sensors, is primarily a function of the quality of the signal processing algorithms being used to process the received signals. In addition to being reliable these algorithms must be able to process the received signals in "real time" if the system is to be an effective weapons system.

Creation of a background data base that can be used to test some of these algorithms has been one of the tasks being performed by the Naval Academic Center for Infrared Technology (NACIT) located at the Naval Postgraduate School (NPS). The Advanced Development Model (ADM) of the AN/SAR-8 was sent to the NACIT in January of 1984 from the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia. The ADM was modified, calibrated and placed in service at NPS in December, 1987. The modified version of the ADM, the Infrared Search and Target Designation (IRSTD) System, is currently operational at NPS. [Ref. 1: pp. 8-12]

One way to enhance the usefulness of the IR data being collected at NPS would be to collect video data concurrently with the IR data. A video image of a portion of the horizon would permit visual identification of IR sources in that region. This additional

tional information could be an aid in the development of the signal processing algorithms for the IRSTD. Accordingly, a decision to proceed with video data collection was made by NACIT, and a camera system was purchased. Components of the system include;

- RCA (TC1005/01), Closed circuit video camera.
- PELCO (AI700), Automatic iris servo.
- PELCO (F1.5X), 1.5 times range extender.
- PELCO (MLZ6DT), Desk top lens remote control module.
- PELCO (PT1250DC), Heavy duty Pan/Tilt servo.
- PELCO (MPTV1510DT), Pan/Tilt remote control unit.
- Panasonic (WV-5410), Video Monitor.

In Ref. 1 Ayers describes the IRSTD's detectors:

> The IR detectors consist of two vertical arrays of sensing elements in the focal plane of the Schmidt telescope. The telescope is rotated so as to sweep the image across the detector arrays. Each array incorporates a column of 90 indium antimonide photovoltic linear detector elements. These two arrays are independent of each other and are covered by filters which pass selected wavebands of IR radiation in the 3 to 5 micrometer range. Each element has the angular dimensions of 2 X .3 milliradians with the larger being its height. Designated as the lead and the lag, these two arrays are separated by about one-half degree in azimuth. [Ref. 1: p. 17]

Thus, as the IRSTD scans the horizon the resulting IR image has a resolution of approximately 10^{-4} radians (0.00573°) in the horizontal plane and 0.23° in the vertical plane. The video system's smaller field of view can be remotely controlled using the control units listed above. Thus, for the video data to be of any use in the development of the signal processing algorithms, the camera's orientation must first be known, and, in order to determine the pixel-to-pixel correlation between the IR image and the video image, the position of the video camera needs to be known with the same kind of accuracy as the IR image. The design and implementation of a position measuring system for this remotely controlled video camera is the subject of this thesis.

B. DESIGN SPECIFICATIONS

The design specifications for this problem were relatively straight forward. The position measuring system needed to meet the following criteria.

- The system should be able to measure the elevation angle (tilt), above and below the horizontal reference plane of the camera over a range of $\pm$ 12°.
- The measured elevation angle should be accurate to within $\pm$ 0.23° .

- The system should be able to measure the bearing (pan), left or right of some arbitrary reference, of the camera over a range of 360°.
- The measured bearing should be accurate to within $\pm 10^{-4}$ radians.
- The output should be displayed in a convenient form. The display should be collocated with the camera servo remote controls, an indoor site approximately 200 meters away from the camera.
- Portions of the measuring system required to be collocated with the camera should be weatherproofed.
- The system must be reliable and should be simple to operate.

II. DESIGN STRATEGY

A. GENERAL

A position measuring system, like any system, is a combination of devices interconnected to perform a certain function. The most basic position measuring system (see Figure 1) consists of only four such devices: a transducer, a signal conditioner, a display device and a power supply. More complicated position measuring systems include those designed to take a number of different measurements either simultaneously or consecutively. Still more complex systems multiplex these various measurements over a single channel to some distant location where they can be processed and displayed. [Ref. 2: pp. 2-14]

The design specifications for the camera position measurement system (subsequently referred to as the "measurement system") required that two measurements, pan and tilt, be taken simultaneously and transmitted some distance to a remote display. Two separate transducers, capable of independent operation, were therefore required. In order for both the azimuth and the elevation to be displayed simultaneously two display devices were also required.

Several pairs of RG-178 coaxial cable were available to transmit signals between the camera servo and the remote control site. Since the cable was available and it was desirable to reduce the system complexity, a decision was made not to multiplex the data over a single channel. Instead, each measurand would have a separate transducer, a dedicated signal processor and a unique display device. Position information for each axis would be transmitted over a dedicated channel.

The physical locations of the transducers and the display devices were dictated by the design specifications; however, there was some flexibility in deciding where to locate the signal conditioner. Site selection was based on an attempt to maximize total system performance and simplicity while ensuring the maintainability and environmental integrity of the signal conditioner. The only advantage to locating the signal conditioner with the camera servo and the transducer would have been to limit the distance that the transducer's output signal would have to be transmitted to the processor. On the other hand, separating the signal conditioner and the transducers would limit the distance over which the conditioned signal would have to be transmitted to the display device. The trade-off here was not clear cut and would probably depend on the specific hardware

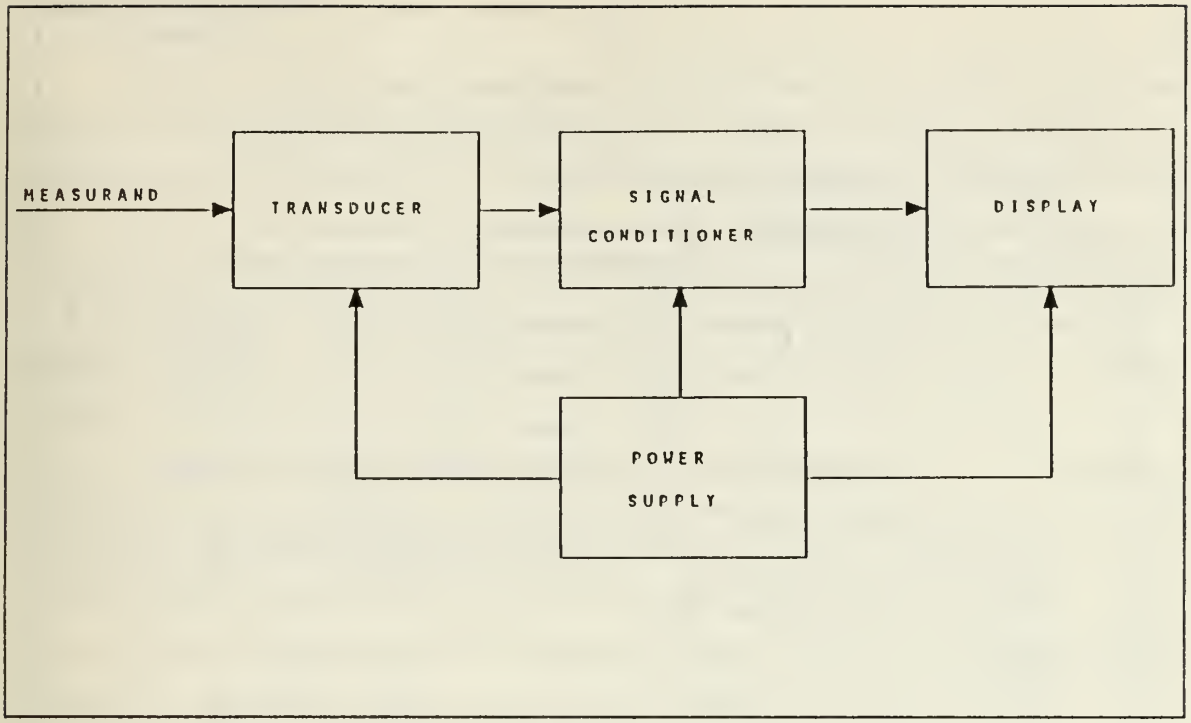


Figure 1. Basic Electronic Position Measuring System: From Ref. 2: p. 2

used and the speed of rotation of the camera servo. There was one significant advantage, however, to collocating the display and the signal processor; since they would both be indoors, the need for weatherproofing the signal processor would be eliminated.

Power was available at both ends of the system, there was therefore no requirement to have a common power supply for the entire system. One supply could be used to provide power to the two transducers, collocated with the camera servo, and a second supply could power the signal conditioner and the displays.

A block diagram of the prototype measurement system is shown interconnected with the camera positioning system in Figure 2. Once this basic system layout had been determined, proper selection of the actual hardware was necessary. The design criteria were the primary consideration in the initial stages of the hardware selection. Final selection of the specific components, however, involved balancing additional factors, such as availability and cost against the system requirements.

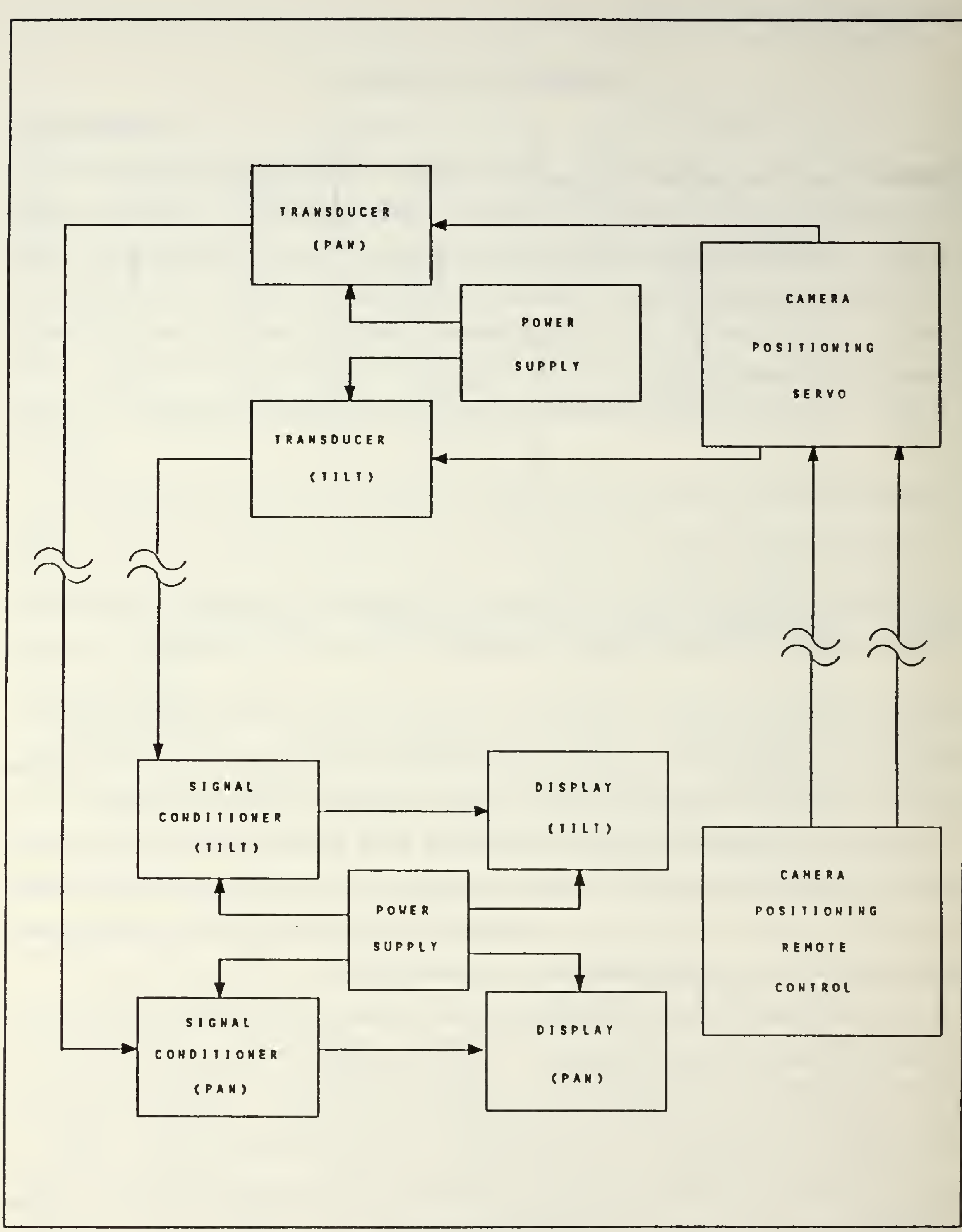


Figure 2. Camera Position Measuring System

B. TRANSDUCERS

1. General

Since in practice most measurement systems do not have the ability to respond directly to the measurand, transducers are used to convert one physical quantity (e.g., angular position) into another, more usable quantity or signal (e.g., an electrical signal) [Ref. 3: p. 1-4]. The transducer is therefore a vital part of any measurement system, and although none of the components of this system could have been chosen independently of the other elements, proper transducer selection appeared to be the key to meeting the design specifications. Thus, selection of a transducer was the next step in the design process.

Using the selection guidelines given by Norton on pages 51-53 of Ref. 2 and the design criteria stated previously, several observations and decisions were made which significantly reduced the number of transducers considered feasible for use in the measurement system. The fact that the servo was capable of rotating the camera left or right, and up or down suggested that the transducer should be capable of detecting both increasing and decreasing angles on both axes. Additionally, since the servo was anticipated to rotate the camera through one 360° arc in the horizontal plane, the transducer used to measure this angle (subsequently referred to as the "pan transducer") needed to have a comparable range capability. The range requirement for the "tilt transducer" (used to measure the elevation angle) was much less restrictive. These factors, angular bidirectional capability and full scale range, eliminated a great number of transducers from the list of candidates.

The list was further narrowed by the accuracy requirements previously specified. Again the accuracy in the horizontal plane placed a much more severe limitation on the selection of a transducer than the accuracy requirements for the vertical plane. The following paragraphs in this section outline the logic used in the selection of the transducers. The factors considered in the selection process included the following;

- The accuracy requirements given in the specifications.
- The ease with which a specific transducer could be installed on the servo.
- The ability to weatherproof the servo and the transducer once the transducer was installed.
- The rotation speed of the camera about the servo axes.
- The extent to which a particular transducer/mounting configuration would modify the measurand.
- Cost effectiveness.

- Availability.
- Signal conditioning requirements.
- The extent to which the selection of a particular transducer would simplify or complicate the modification or expansion of the measurement system.

2. Transducer technologies

Displacement transducer technologies fall into three very broad categories depending on whether they are capable of measuring linear or angular displacement, or both. Some technologies could be eliminated immediately since they were clearly not suited for measuring angular position. Strain gauge displacement transducers, inductive displacement transducers and vibrating-wire displacement transducers are examples of such devices. The following paragraphs briefly describe the different transducer technologies which were investigated. Table 1 on page 18 summarizes the salient points of the discussion. [Ref. 2: pp. 90-117].

a. Reluctive Displacement Transducers

The rotary variable differential transformer (RVDT), which operates by detecting a change in the reluctance between coils, offers excellent resolution, dynamic characteristics, linearity and life expectancy [Ref.3: p. (2-14)]. Figure 3 shows a schematic diagram and a simplified cross-section of an RVDT. The ferromagnetic, cardioid-shaped core is attached to a shaft as shown. As the shaft rotates, the inductive coupling between the primary and each of the secondary coils changes. When the cam is symmetric with respect to the two secondary coils, their output voltages are equal but opposite in phase which results in a differential output voltage of zero. As the shaft rotates away from this "null" the differential output voltage varies as shown in Figure 4. The linear region of the curve is limited to the angles between $\pm 40°$ of the reference. Thus, the RVDT could not be used on the Pan axis. It was however, initially considered as a candidate for the Tilt transducer. [Refs. 2: pp. 93-99, 3: pp. (9-10)-(9-13) and 4: p. 19]

Another type of reluctive displacement transducer is manufactured by Farrand Controls. Their INDUCTOSYN rotary position transducers have accuracies to $\pm$ 1.5 arc sec ($\simeq (4 \times 10^{-4})°$). Unfortunately, these devices are 11.89 inches in diameter, and mounting them on the camera servo would have been extremely difficult, if not impossible. [Refs. 2: pp. 89-111, 5]

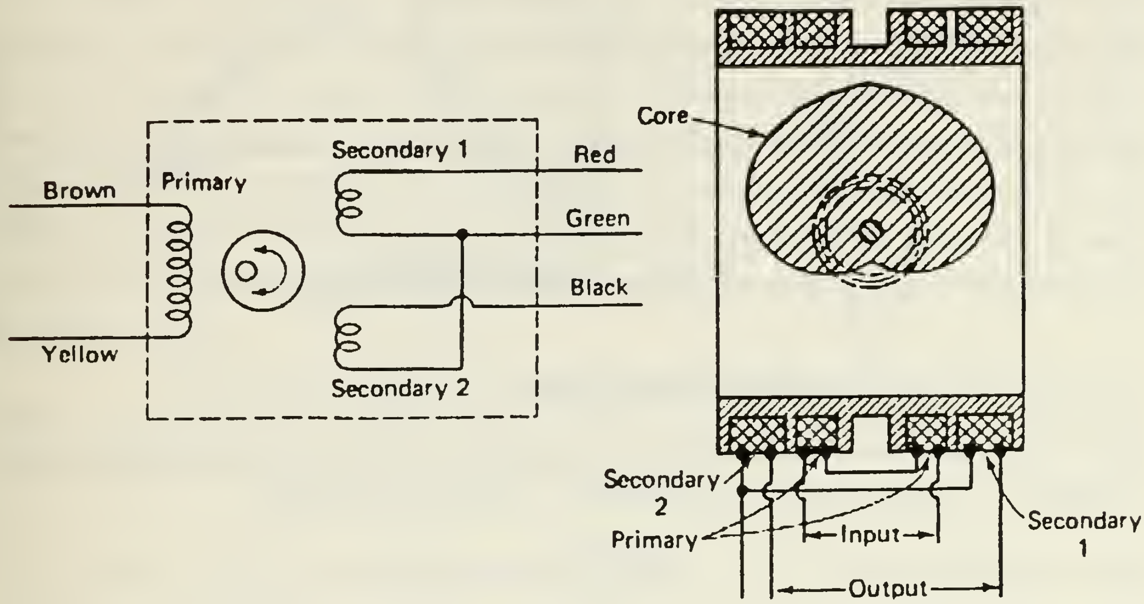


Figure 3. RVDT Schematic: From Ref. 2: p. 98.

b. Capacitive Displacement Transducers

Angular displacement can also be measured by coupling the rotating component to the shaft a of variable capacitor in the manner shown in Figure 5. Lenk describes the operation of the capacitive displacement transducer quite succinctly.

> The capacitor ... consists of a metal plate that moves between two fixed metal plates as a shaft is rotated. The three plates, and the air between them, form a capacitor with a capacitance that varies in proportion to the degree to which the plates are meshed. When the plates are completely meshed, the capacitance is at its maximum. When the plates are completely unmeshed, the capacitance is at minimum. [Ref. 4: p. 18]

Capacitive displacement transducers offer many of the advantages of reluctance displacement transducers. They have an effective range of about 300° which, while better than the RVDT's range, is still not adequate for the pan axis [Ref. 4: p. 18]. Additionally they are more sensitive to changes in the ambient temperature. Since the

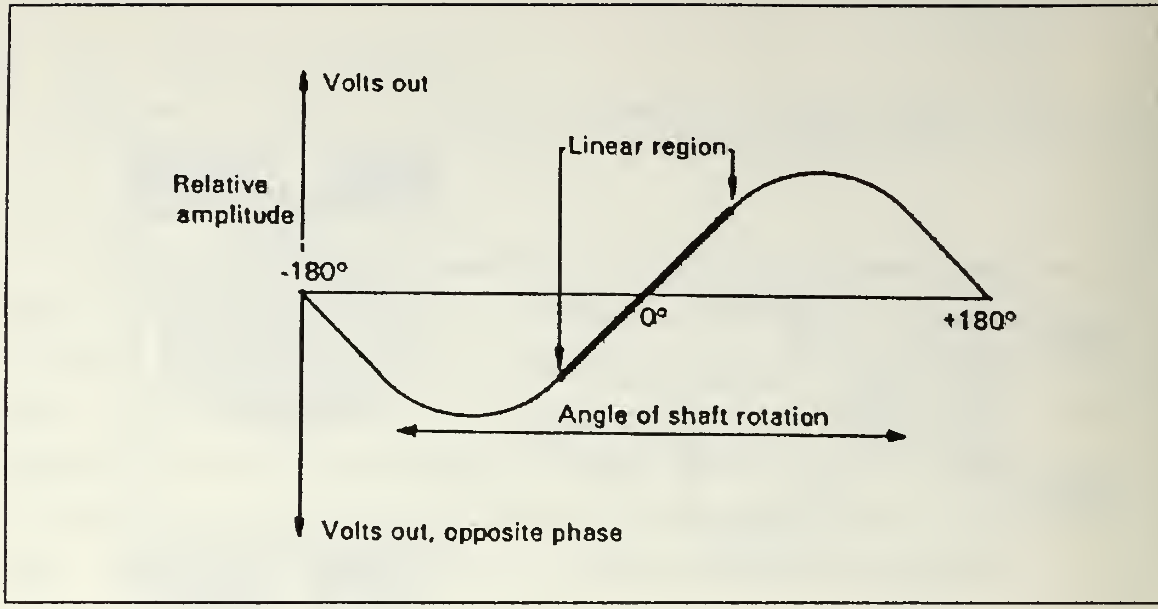


Figure 4. RVDT Output Characteristics: From Ref. 2: p. 95.

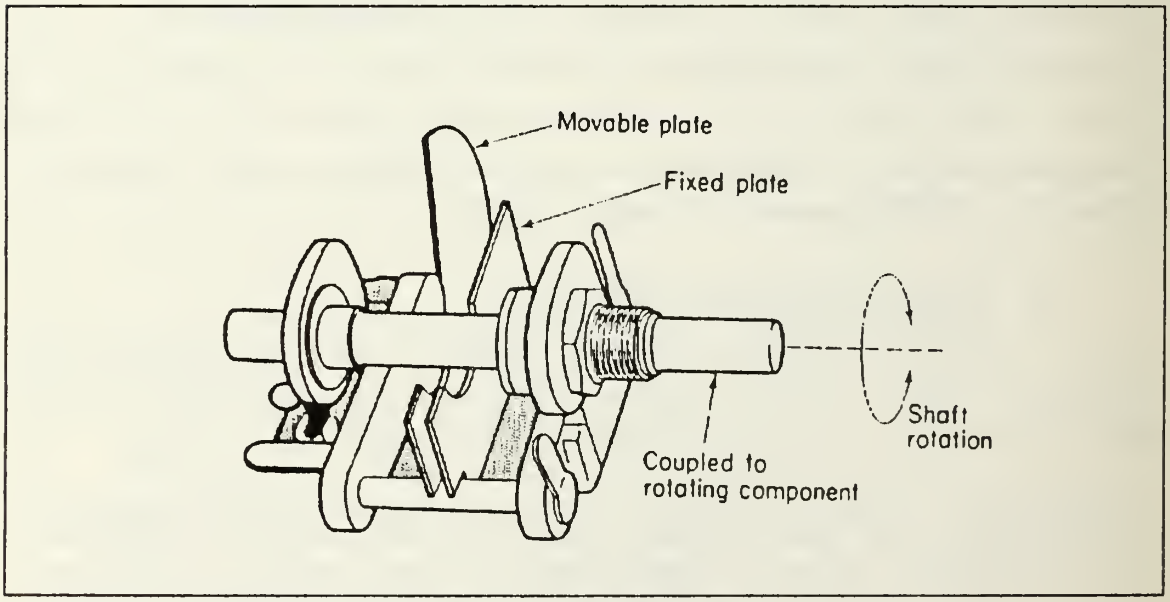


Figure 5. Capacitive Displacement Transducer: Ref. 4: p. 18.

measurement system was being designed to be used outdoors, the use of a capacitive displacement transducer would have required the addition of a temperature compensator in the design. While possible, this would have increased the system complexity considerably. [Ref. 2: pp. 90-91]

c. Potentiometric Displacement Transducers

Another very common and relatively simple family of transducers operate by measuring the change in resistance caused by a change in the measurand. There are a wide variety of such devices available. The basic form of potentiometric angular displacement transducers uses a resistance element, formed into an arc, and a movable electrical contact that rotates about the axis of interest. By measuring the change in resistance that results from a change in position, one is able to determine the angular displacement. The resistive element is typically a wirewound element, the resolution of which is determined by the number of turns per unit length of the resistance element. The angular resolution can be increased by increasing the turn density (wires/degree) of the potentiometer.

The practical limit for wire spacing on wirewound elements according to Ref. 6 is between 500 and 1000 turns per inch. From Figure 6 one can see that this limits the angular resolution for a single-turn device to

$$\Delta\theta(\mathrm{rad}) \simeq \tan\left(\frac{\Delta x\,(\mathrm{in})}{R(\mathrm{in})}\right) \tag{1}$$

Therefore,

$$\Delta\theta(\mathrm{rad}) \simeq \frac{2\Delta x}{D} = \frac{0.002(\mathrm{in})}{D(\mathrm{in})} \quad . \tag{2}$$

To achieve the 10^{-4} rad resolution, specified for the Pan axis, with a single turn potentiometer would therefore require a 20 in diameter potentiometer. Mounting a device this large on the camera servo was simply not feasible. Potentiometers are, however, available with multiple turns. Shaped in a helix fashion similar to that shown in Figure 7, the total length of the potentiometer can be increased, which in turn increases its resolution, without increasing the diameter of the device.

Increasing the resolution of the potentiometer by increasing the turn density in any of the manners described above, however, increases the output impedance of the device, which leads to increasing nonlinearity between the measurand and the transducer

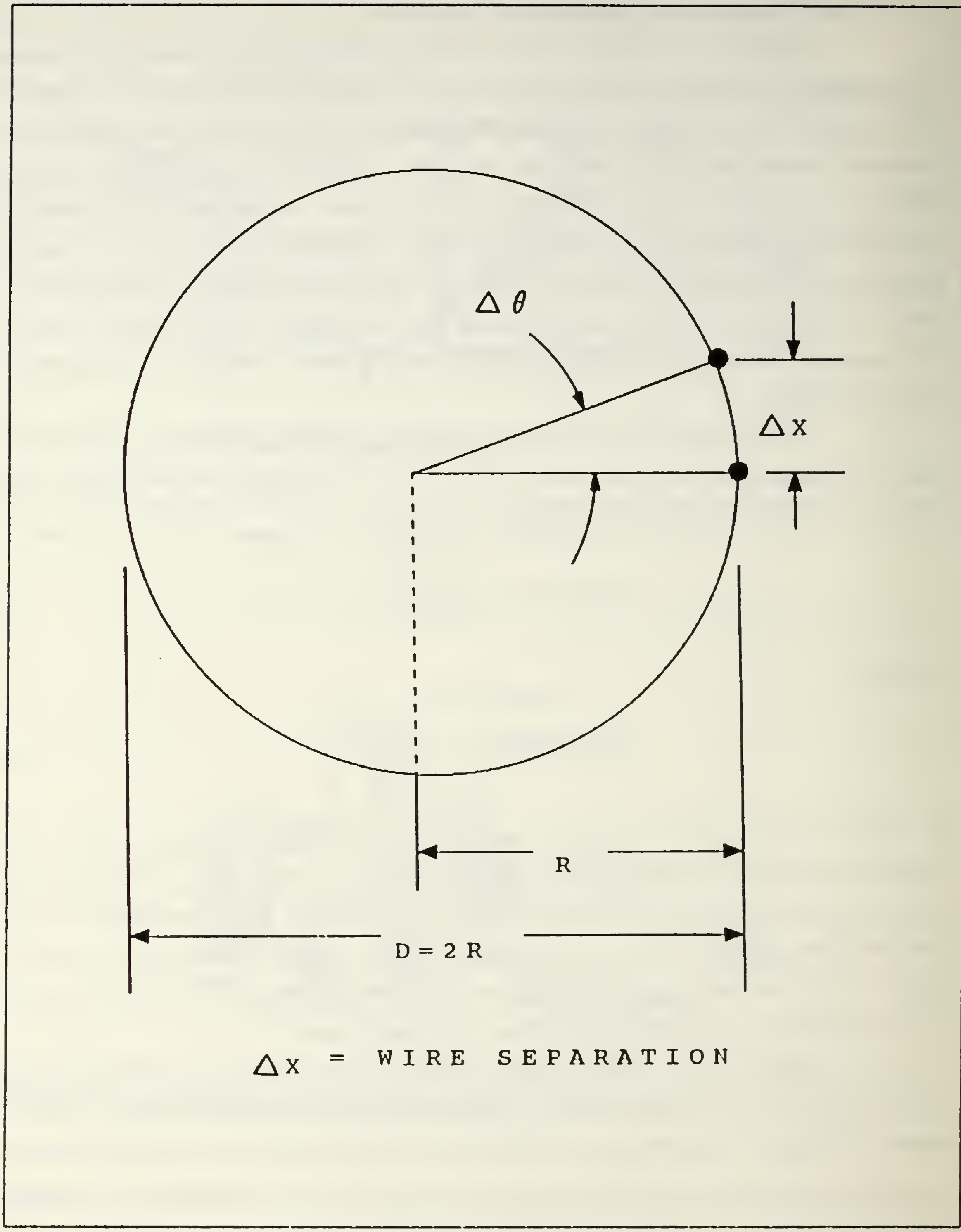


Figure 6. Geometry of an Angular Potentiometric Transducer

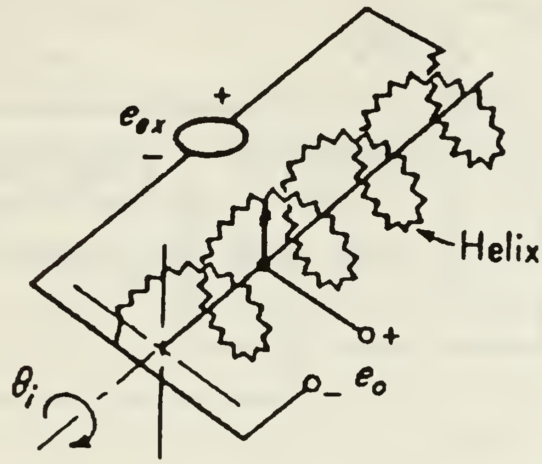


Figure 7. Multiturn Potentiometer: From Ref. 6: p. 218

output. The nonlinear relationship can be seen by analyzing the circuit shown in Figure 8. In the diagram the following variable definitions apply:

- e_X = Input voltage,
- e_o = Output voltage,
- R_p = Total resistance of the potentiometer,
- R_m = Meter resistance,
- x_t = Total range of the potentiometer, and
- x_i = Actual displacement of the potentiometer.

Assuming that R_p is uniformly distributed over x_t, analysis of the voltage divider circuit gives,

$$\frac{e_o}{e_X} = \frac{1}{\frac{x_t}{x_i} + \left(\frac{R_p}{R_m}\right)\left(1 - \frac{x_i}{x_t}\right)} \quad . \tag{3}$$

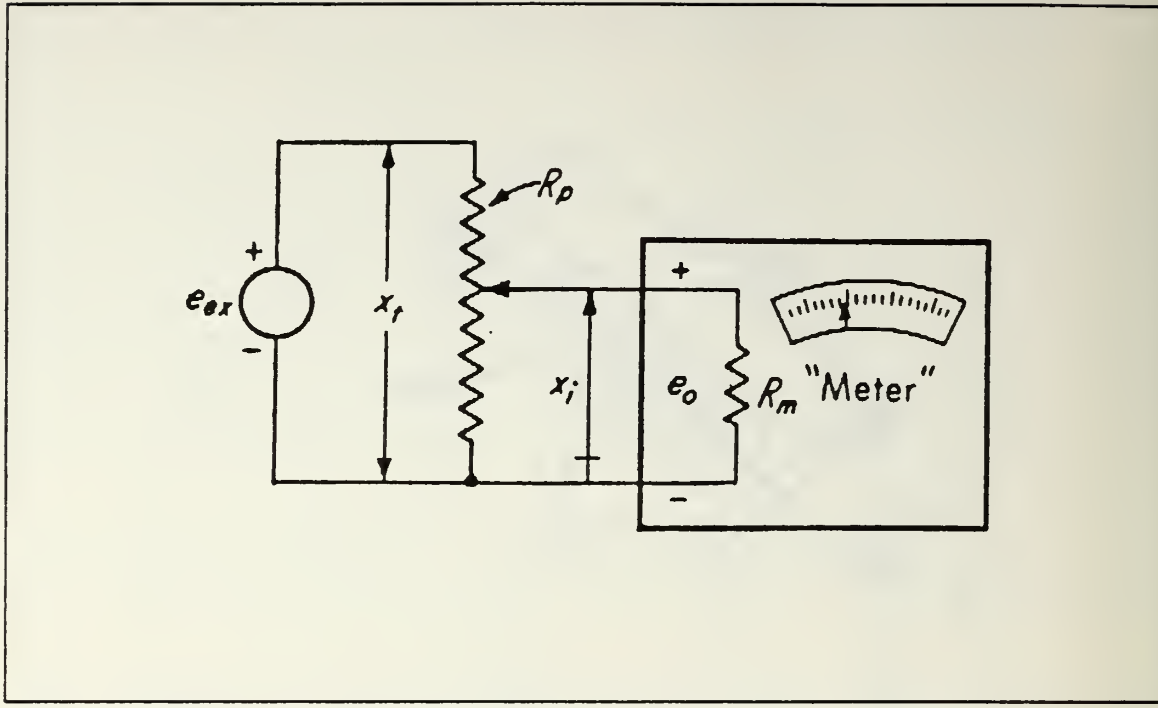


Figure 8. Potentiometric Transducer: From Ref. 6: p. 219

Thus, the ideal (i.e., linear) relationship,

$$\frac{e_o}{e_X} = \frac{x_i}{x_t} \ , \tag{4}$$

is true only when $R_p/R_m = 0$, and since $R_p \neq 0$, and $R_m \neq \infty$, the nonlinear relationship in (3) will always exist. Doebelin states that "for values of $R_p/R_m < 0.1$ the position of maximum error occurs in the neighborhood of $x_i/x_t = 0.67$, and the maximum error is approximately $15(R_p/R_m)$ percent of full scale." [Ref. 6: p. 218] Other potentiometric transducers, which use a resistive element made of carbon film or a conducting plastic, are not subject to the same kind of resolution limitations as wirewound devices; however, they do have high output impedances and the corresponding nonlinearities described above. [Ref. 6: pp. 217-224]

A high quality multiturn potentiometer used in conjunction with a high quality voltmeter offered one possible solution to the design problem. However, the nonlinearity of this arrangement was a significant disadvantage, and the primary reason why potentiometers were not used.

d. Encoders

The angular displacement transducer, referred to in general as an angular encoder or shaft encoder, converts an angular displacement into a digital signal without the use of an analog-to-digital converter. In today's increasingly digital world this can be a distinct advantage.

There are three different transduction methods used in encoders. Magnetic encoders use a pattern made from magnetized and nonmagnetized segments and one or more magnetic sensors that register as either "1's" or "0's" depending on the magnetic characteristics of the section that they are adjacent to. Brush-type encoders are similar, but the sections are made of conducting and nonconducting materials. The conductors are all tied to a common source and the "sensor" is one or more brushes connected to the output. When the brush is in contact with one of the conductors the output is "on" and when the brush is in contact with an insulator the output is "off". Optical encoders (See Figure 9) use a pattern of opaque sections marked on an otherwise transparent disk. A light emitting diode (LED), or other light source, is placed on one side of the disk, and as the disk rotates a light sensor on the other side of the disk "sees" periods of dark and light which it converts into a digital signal. [Ref. 2: p. 106]

Angular encoders are further categorized as either absolute encoders or incremental encoders. Absolute encoders, similar to the optical encoder shown in Figure 9, use a multitrack pattern on a code wheel to produce a unique coded output signal for each incremental change in the measurand. These wheels use a variety of codes, including binary code, binary-coded decimal (BCD) and Gray code, to determine the shaft position. The resolution of an absolute shaft encoder is limited by the number of tracks on the disk and the type of code used. A simple binary or Gray code encoder, which are more efficient than the BCD encoders, with N tracks has an optimum angular resolution of

$$\Delta\theta = \frac{360°}{2^N} \quad . \tag{5}$$

Thus, to achieve the desired resolution of 10^{-4} radians on the Pan axis with an absolute encoder would require a code wheel with $N \geq 16$. Since the output from the encoder is unique for each position, these devices are not affected by power outages, and the requirements for a signal processor for such a device would be limited to a simple decoding circuit. These encoders can measure angles of up to 360° without ambiguity.

Incremental encoders use a code wheel which has only one track. As the shaft of the incremental encoder rotates the output from the encoder is a series of equally spaced pulses. These pulses can then be used as an input signal to an up/down (U/D) counter of some sort. The output from the counter is an indication of the displacement of the axis from some predetermined reference. The resolution of an incremental encoder is a function of the number of pulses the code wheel generates per revolution and is given by;

$$\Delta\theta = \frac{360°}{n \times PPR} \tag{6}$$

where PPR is the number of pulses per revolution of the code wheel, and n is the number of revolutions that the code wheel makes per revolution of the axis of interest. If the incremental shaft encoder was mounted on the shaft of interest (n = 1) at least 62,832 PPR would be required to ensure a resolution of 10^{-4} radians.

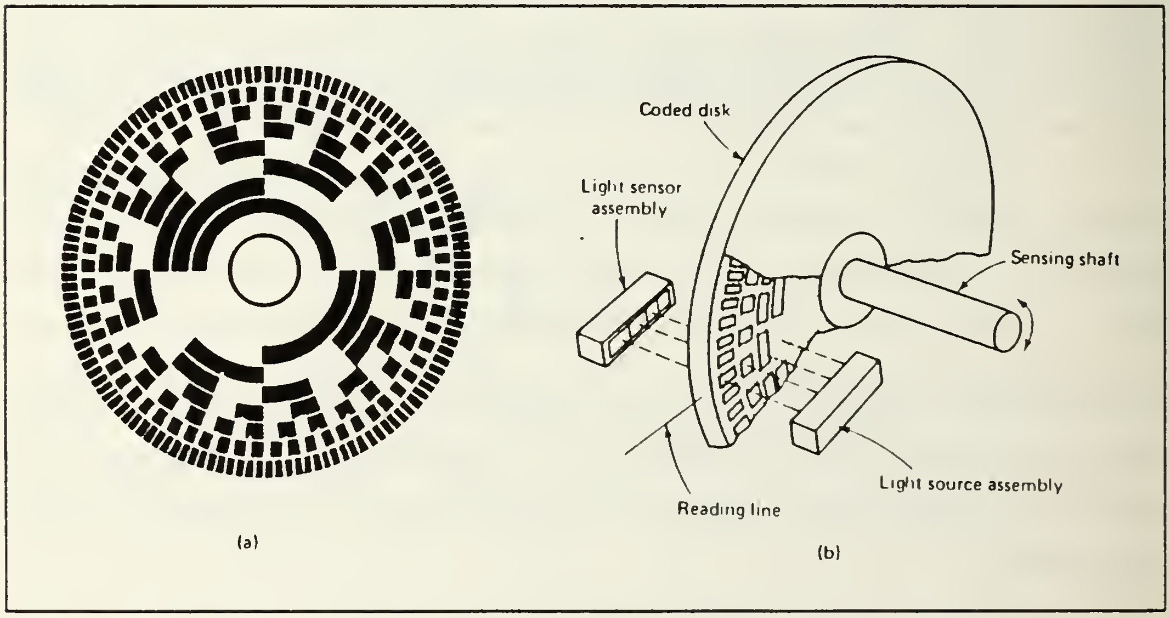


Figure 9. Absolute Photoelectric Angular Encoder: (a) typical code disk; (b) encoder elements. From Ref. 2: p. 107.

Shaft encoders currently range in price from less than $100.00 to several thousand dollars depending on their capabilities and the method of transduction used. Litton Encoder's Model 60 absolute shaft encoder uses a natural binary code, has 15 tracks (0.1917 mrad resolution) and is available "off the shelf" for approximately $3000.

Other absolute encoders with comparable resolutions are available at similar prices. No incremental encoders were found which offered the same kind of resolution as Litton's Model 60; however, because they are not limited to one revolution of the axis, the resolution of an incremental encoder can be improved by a factor of n by causing its code wheel to rotate n times for every rotation of the axis of interest. Incremental encoders with 1024 PPR are available from a variety of manufacturers for about $100 each. Connecting such a device to the axis of interest via a gear train with a 50:1 ratio would theoretically result (from (6)) in a resolution of 0.1227 mrad. Incremental encoders do require more complex signal processing than absolute encoders, and they are affected by power shut-off. Additionally, unlike absolute encoders, any missed or erroneous count that occurs with an incremental encoder will cause a persistent error. [Ref. 7: p. 16]

After considering the measurement system performance criteria and the capabilities and limitations of the various transducers, the use of an incremental, optical shaft encoder appeared to be the best selection for the transducer for each axis. This decision involved balancing the various advantages and disadvantages of the different transducers. The following list gives a summary of the key considerations in this decision.

- Small, lightweight, highly accurate and relatively inexpensive models were readily available. Being small and lightweight suggested that mounting and weatherproofing the transducers in the camera servo should not be too difficult.
- Absolute encoders offer almost all of the advantages of the incremental encoders; they are not affected by power outage, they require less complex signal processing and one time counting errors do not persist. However, these features did not seem to justify the additional price of an absolute encoder.
- Linearity and loading problems associated with the potentiometric displacement transducers were avoided.
- Direct conversion of the measurand into a digital signal precluded the requirement for an A/D converter. (This would have been a disadvantage had the use of an analog signal conditioner been anticipated.)
- Using two identical transducers, each capable of meeting the specifications for the pan axis, would reduce system complexity while still ensuring that the design specifications were met.

C. MOUNTING THE TRANSDUCER

Once the decision to use an incremental optical shaft encoder was made, selection of a specific model remained. Before selection of an actual piece of hardware could be

Table 1. ANGULAR DISPLACEMENT TRANSDUCERS

TRANSDUCER DESIGN	RANGE	RESOLUTION	LINEARITY	OTHER
Reluctive Displacement (RVDT)	0° –360°	Theoretically infinite; Limited by the signal conditioner.	Poor beyond ± 40°	
Reluctive Displacement (Farrand's INDUCTOSYN)	0° –360°	$\pm (4 \times 10^{-4})°$	Good	Large size limits usefulness with the camera measuring system.
Capacitive Displacement	0° –300°	Theoretically infinite; Limited by the signal conditioner.	Good	Temperature sensitive
Potentiometric Displacement	0° –3500°	Device dependent	Device dependent	The trade-off between range resolution and linearity due to the loading effect of the noninfinite impedance of the signal conditioning devices used.
Absolute Encoders	0° –360°	$\frac{360°}{2^N}$	Good	No A D conversion required. Insensitive to power shut-off.
Incremental Encoders	$\pm \infty$	$\frac{360°}{n \times PPR}$	Good	Simple. Requires more signal processing than absolute encoder but is less expensive.

done though, one additional practical consideration had to be made; where and how could a transducer be mounted in or on the servo in order to measure the position of the Pan and Tilt axes?

The physical layout of the camera positioning servo made direct connection of any type of transducer to the axes of interest virtually impossible without major modification of the servo itself. Major modification of the servo would have been expensive, time consuming and outside the scope of this thesis. It was not considered an option in this case. Measurement of the Pan and Tilt axes' displacements was most readily accomplished indirectly. Each axis of the servo is positioned by a separate dc motor via a gear train. By mounting the shaft encoder code wheels to the sprockets (items 42 and 43 in

Figure 10) which are each attached to one of the worms, an indirect measurement of the position of each of the wormgears (items 5 and 7 in Figure 10) was possible. This approach, made necessary by the servo design, was a mixed blessing.

The backlash in a worm-wormgear connection will cause the position of the worm to be different for any given wormgear position, depending on whether that position is approached from a clockwise or a counterclockwise direction. In order to correctly determine the displacement of the wormgear by measuring the displacement of the worm, the amount of backlash present must be known (i.e., would have to be determined experimentally) and accounted for by the measurement system. This nonlinear source of error would not have been a concern if the servo was only required to rotate in one direction. This was not the case, however, and hysteresis eventually was determined to be the largest single source of error in the measurement system. A more complete discussion of this topic is included in Chapter IV of this thesis.

Assuming for the moment that the effects of the backlash in the gears could have been completely compensated for, mounting the shaft encoders on the worm provided a measurement advantage analogous to the mechanical advantage afforded by the gear train. Initial measurements indicated that each of the worms turned through 18,000° (50 × 360°) for every 360° rotation of the corresponding wormgear. This meant that a shaft encoder with 100 divisions per 360° attached to the worm axis could do the same job as a 5,000 division per 360° encoder attached to the wormgear axis.

D. SELECTING AN OPTICAL SHAFT ENCODER

Once the basic decisions to use incremental optical shaft encoders and to mount the encoders on the worms inside the servo housing had been made, selection of the specific pieces of hardware was relatively straight forward and was primarily a matter of convenience and expediency.

Returning to the design specifications for a moment; the most stringent requirement was to be able to measure the position of the pan axis to within $\pm(5.73 \times 10^{-3})°$. To determine the required resolution for the optical shaft encoder, the following calculations were performed.

First,

$$\frac{360°/\text{Revolution}}{5.73 \times 10^{-3}°/\text{Division}} \simeq 62{,}827 \, \frac{\text{Divisions}}{\text{Revolution}} \quad . \tag{7}$$

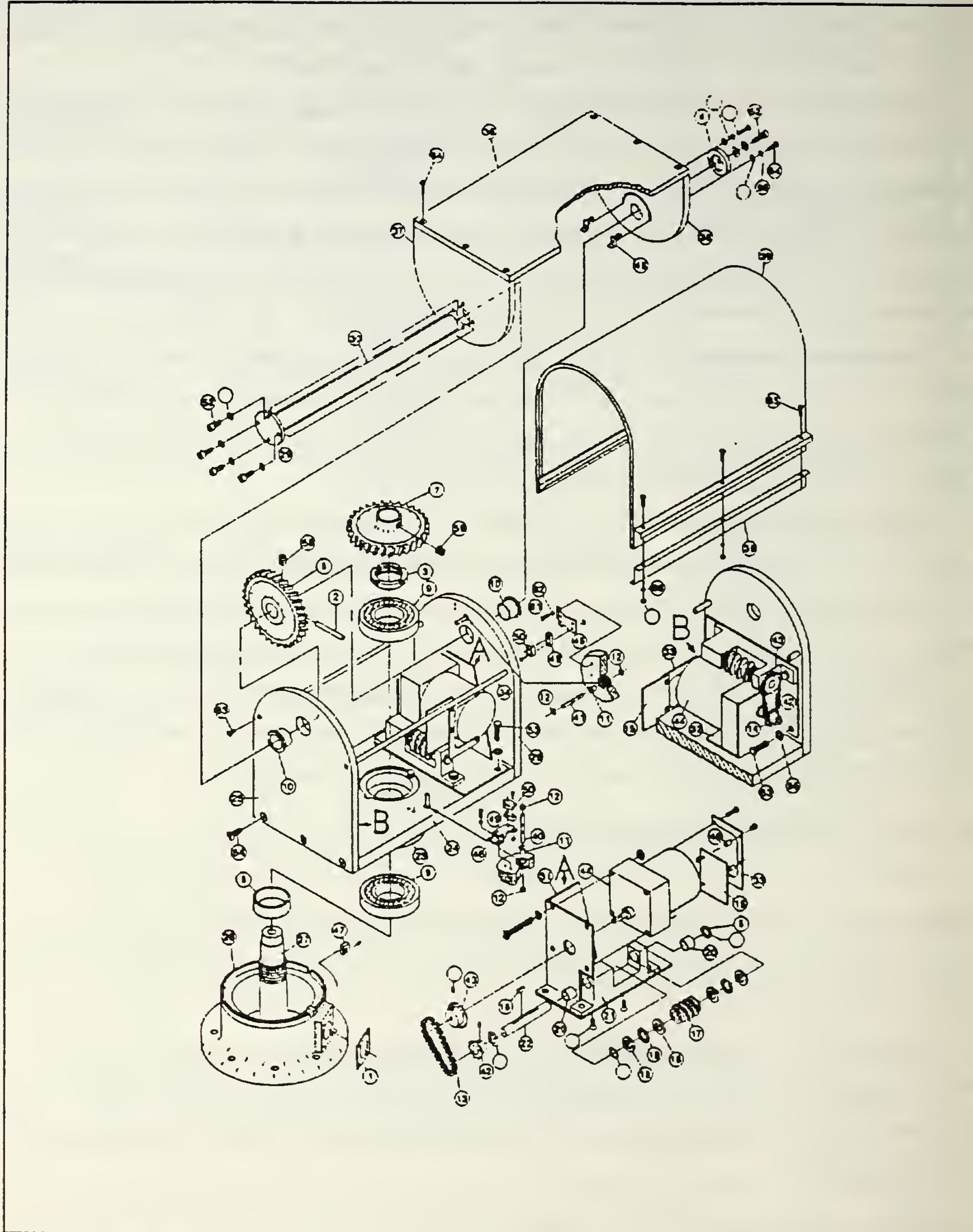


Figure 10. Camera Servo: From Ref. 8: p. 12.

Then, considering the 50:1 gear advantage,

$$\frac{62{,}827}{50} \simeq 1257 \frac{\text{Divisions}}{\text{Revolution}} \quad . \tag{8}$$

The task therefore was to find an optical shaft encoder capable of detecting bidirectional rotation with at least 1257 Divisions/Revolution in a package small enough to mount in the servo housing on the worm axis. There was no absolute size limitation; however, due to the construction of the servo it was desirable to find an encoder that was no more than 3 in. in diameter and no more than 1.5 in. in width. The companies that make shaft encoders are capable of custom building devices to meet a customer's specific needs. However, the prices are high, and the lead times are long for these special order parts. The encoder for this system needed to be reasonably priced and readily available to ensure timely completion of the project and to facilitate replacement, if necessary, in the future.

Optical shaft encoders are manufactured by numerous companies including Litton, Honeywell, BEI, IVO and Hewlett Packard. Sales literature from these companies was reviewed prior to making a decision on the specific shaft encoder model to be used. Incremental optical shaft encoders with resolutions that range from one pulse per revolution (PPR) to 2540 PPR are available off the shelf from one or more of these companies. While evaluating sources of supply, incremental optical shaft encoders were also found in use in various laboratories and shops in the Electrical Engineering and Physics Departments at the NPS. Encoders immediately available from stock included two Vernitech 1200 PPR (model VOE-23-1200-AI-LD5-2L1-1603-2) encoders from the Physics Department and two Hewlett Packard (HEDS-6000/J06) encoders from the Electrical Engineering Department. The use of the Vernitech encoders was ruled out because they were unable to detect bidirectional movement without increasing the complexity of the signal conditioning subsystem. Additionally, technical literature requested on two separate occasions from Vernitech was never received.

The HEDS-6000/J06 encoders have a resolution of 1024 PPR. Each encoder provides displacement information in the form of TTL logic level signals via two output channels. When the encoder is properly adjusted the two output signals have a 90° phase difference. This quadrature phase relationship permits these encoders to detect bidirectional displacements. Rotation in one direction will cause Channel A to lead

Channel B (in phase), while rotation in the other direction will cause Channel B to lead Channel A. [Ref. 9: p. 2]

The presence of two output channels in quadrature phase has an additional benefit that is useful in some applications. Since the amount of position information has essentially been doubled, if the signal conditioner is designed to detect both the leading and trailing edges of one of the output channels the resolution of the measurement system can be doubled. The difficulty with using this technique is that multiple oscillations about a single point cannot be detected as such. If the camera were to oscillate less than one half of a pulse width about a transition the signal conditioner would detect and erroneously count the multiple transitions. [Ref. 7: pp. 13-16]

With 1024 PPR, which is less than the 1257 PPR required to meet the 0.1 milliradian accuracy specification on the pan axis, the maximum resolution available, if the HEDS-6000 was attached to the worm, can be calculated as;

$$\frac{360^\circ}{(50 \times 1024)} = (7.03125 \times 10^{-3})^\circ \text{ Pulse}^{-1} \ . \tag{9}$$

Although this was not sufficient to satisfy the pan axis resolution specification of $(5.73 \times 10^{-3})^\circ$Pulse,$^{-1}$ all of the other performance criteria could be satisfied. The trade-off seemed reasonable and was approved prior to proceeding further with the system design.

E. THE DISPLAY

Selecting a method to display the final system output was certainly the least demanding task required in the design of the system. With an expected resolution on the pan axis of approximately 0.007° over a range of 360° (a ratio of about 1:51,500) an analog display seemed out of the question. A five or six digit digital display on the other hand offered a simple, reliable and cost efficient means of presenting the output. Constructing the displays from individual, seven-segment, common anode, LED devices, and the appropriate display drivers was a straight forward task.

F. THE SIGNAL CONDITIONER

Anticipating the use of two incremental shaft encoders as the transducers for the measurement system and the use of digital readouts as the display devices significantly reduced the number of possibilities for the signal conditioning subsystem. In addition to the hardware and software described in each of the subsequent discussions, each

technique listed here would require an edge detector to detect the transitions in the TTL signals from the shaft encoders.

- Up/down counter with table look-up.
- Up/down counter and multiplication.
- Add/subtract.
- Microcomputer.
- Microprocessor.

1. Up/down (U/D) counter with table look-up

This technique would involve the use of a shift register, some associated logic, an U/D counter and a table look-up device such as an erasable programmable read only memory (EPROM). The shift register would serve as a hardware buffer that could be used to account for the hysteresis introduced by the worm-wormgear assembly. The length of the buffer would have to be determined experimentally. The logic associated with the shift register would determine the "validity" of each transition (count) signal from the edge detector by checking the contents of the shift register and comparing the current direction of rotation with the previous direction of rotation. Whenever the logic detected a change in rotation direction, or a partially full, or a partially empty buffer (depending on the direction of rotation), the transition would not represent a "valid" count since any of these conditions would indicate that the transition was due to a change in the position of the worm without a corresponding change in the position of the wormgear. Thus, the present transition would be the result of hysteresis due to the backlash in the gear train and the transition would be "invalid". Such a transition would cause the contents of the hysteresis buffer to be modified appropriately. A more complete discussion of this topic is contained in Chapter IV. The shift register and associated logic could be built from common TTL devices readily available at the NPS.

Once a count had been determined to be valid, an U/D counter would be used to keep a running total of the number of counts. Again, such a device could be built using readily available TTL devices such as the 74LS168A, Synchronous 4-Bit Up/Down Decade Counter, or the 74LS169A, Synchronous 4-Bit Up/Down Binary Counter. The output from the U/D counter would then be used as an address to "look up" a predetermined number stored in an EPROM.

This design approach was considered relatively straightforward, and at least initially seemed like a viable option. Its major advantage was that it was conceptually quite simple. This simplicity had a price though; it would have been very hardware in-

tensive and consequently would have been a very inflexible design. For example, if at a later date the use of an arbitrary reference was desired, additional hardware would have to be added to the signal conditioner so that the counter could be initialized to the arbitrary starting point. Since all of the processing would have to be done in hardware, even a minor modification in the system could necessitate a major design revision. Another consideration was that saving in excess of 51,000 unique positions in the EPROM presented a nontrivial problem that would need to be solved if this technique was used.

2. Up/down counter and multiplication

This is very similar to the previous case, differing only in that instead of looking up a predetermined position, in a memory device, a multiplier would be used to multiply the output of the U/D counter by a predetermined constant. As an example, if experimental results indicated that the shaft encoders generated one pulse for every 0.00703125° that the camera was displaced, then each time a valid count was received, the updated count would need to be multiplied by 0.00703125 in the final stage of the signal processor. The result would be the new position. Again, while conceptually simple this idea had some significant disadvantages. Even more hardware intensive than the first approach, this design would also have extremely limited flexibility.

Accomplishing the multiplication would have posed a formidable task. The scale factor would have to be written as some integer (e.g., 0.00703125 would become 703125, or 70323, or 7031, etc.) depending on the desired accuracy. The count, already an integer, would be multiplied by the constant and the correct position of the decimal point would have to be determined. Locating the decimal point would be a relatively simple task, but multiplication of two numbers such as 51,000 and 70,313 would not be as easy. At least one 16 bit by 16 bit binary multiplier (i.e., TRW's MPY016H) is currently available, but since the number 70313 cannot be represented in binary by less than 17 bits, the multiplication could have been accomplished in either of two ways. One solution would have been to perform the multiplication in two or more stages. Alternatively, 70313 could be "rounded" to 7031. The second option would create a cumulative round-off of about $(1.28 \times 10^{-3})°$ per 360° rotation (assuming 51,200 pulses per 360°). This round-off error would probably have been acceptable, but the complexity and limited flexibility of either multiplication scheme made the U/D counter and multiplication an unacceptable candidate for the signal processing subsystem.

3. Add/subtract

A third design concept considered the elimination of the U/D counter altogether. The same logic proposed for use in the previous two designs could have been

used to check the validity of a count and to determine the direction of rotation. However, instead of valid counts being sent to an U/D counter as before, these counts would now signal an adder to add or subtract a predetermined constant from the running total. Just as before, this simple idea could probably have been made to work at least once, but its usefulness as a part of a larger system would certainly have been limited. The large number of components required to realize this design would have increased the probability of failure, complicated troubleshooting and reduced overall flexibility.

4. Microcomputer

If the signal processing subsystem was built around a microcomputer (PC), virtually all of the disadvantages associated with the previously discussed approaches would be eliminated. Since all of the logic could be implemented in software, modifications to the system would be relatively simple to make, and the system's flexibility would be enhanced. However, dedicating a microcomputer, even an inexpensive model, to the signal processing tasks for this measurement system was considered overkill, and timesharing with one of the PC's already in service was possible, but not considered practical or convenient since these microcomputers had already been dedicated to a variety of tasks.

5. Microprocessor

One final option for the signal processor remained. Microprocessors are relatively inexpensive and powerful and are available in a wide variety of makes and models. If a microprocessor was used instead of a microcomputer or a straight hardware processor, the "nice to have" requirements such as flexibility, ease of modification and capacity for expansion, as well as the required signal processing functions could all be satisfied. On the other hand, microprocessors have one distinct disadvantage; they are not user friendly. The use of a microprocessor implied countless hours spent tracking individual bits, debugging assembly language code, studying timing diagrams, etc.. No matter how distasteful the thought, however, a microprocessor was clearly the best way to perform the signal processing functions of the measurement system.

As with the selection of the transducer, once the basic design approach had been determined, selection of a specific device was a relatively straight forward task. The choice of one microprocessor over another was a function of the processor's ability to perform the required tasks, cost effectiveness and availability. Motorola's MC68705U3 seemed to satisfy all of these requirements. The MC68705U3 is a four kilobyte EPROM microprocessor, built using HMOS (high-density NMOS) technology with an eight bit architecture. The "68705" operates on a 5.0 volt dc supply, has 112 bytes of on chip RAM, four vectored interrupts, 24 TTL/CMOS compatible bidirectional I/O lines (eight

lines are LED compatible), eight dedicated input lines and an internal eight bit timer with a seven bit programmable prescaler. [Ref. 10: p. 1]

In Ref. 10 Motorola advertises the following software features:

- Programming language similar to the 6800 family.
- Byte efficient instruction set.
- Easy to program.
- True bit manipulation.
- Bit test and branch instructions.
- Versatile interrupt handling.
- Powerful indexed addressing for tables.
- Versatile index register.
- A full set of conditional branches.
- Memory usable as registers/flags.
- Single instruction memory examine/change capability.
- Ten powerful addressing modes.
- All addressing modes apply to EPROM, RAM and I/O.

One key advantage to using the MC68705U3 was that one of the microprocessors, and a Motorola M68705EVM (the evaluation/programming module for the M6805 family of devices) were both available for immediate use at the NPS. The fact that the 68705 utilized HMOS technology suggested that it should be a relatively low cost microprocessor. In fact, except for the price of a phone call, a second microprocessor was obtained free of charge from a local electronics wholesaler. Additional microprocessors, to be used as replacements and as backup devices were ordered for about $20.00 each.

One potential problem with using a microprocessor begged checking prior to proceeding. Initial measurements of the camera's maximum rotation velocity produced the following results.

$$\omega_{PAN(\max)} \simeq 1.0 \text{ rpm} \tag{10}$$

$$\omega_{TILT(\max)} \simeq 0.5 \text{ rpm} \tag{11}$$

Again the requirements for the pan axis presented the most stringent design limitations. Since the optical shaft encoders were anticipated to deliver 51,200 PPR (1024×50) the

microprocessor on the pan axis had to be capable of processing 51,200 pulses/minute (1.172 ms / pulse). The MC68705U3 is designed to operate with an oscillator frequency (f_{osc}) of between 0.4 MHz and 4.4 MHz and has an instruction cycle time ($4/f_{osc}$) of between 0.950 μs and 10 μs. Assuming that a 4.0 MHz clock was used, the instruction cycle time would be 1.0 μs. This would mean that the processing of each pulse would have to be accomplished in no more than 1172 instruction cycles to ensure that no pulses would be missed.

III. DESIGN

A. GENERAL

The schematic diagrams for the measurement system are shown in Appendix A; Appendix B contains copies of the printed circuit board plans. Before describing the detailed operation of each of the individual components of the measurement system, a brief overview of its basic theory of operation is in order. The measurement system is actually two separate systems operating independently. The system designed to measure the azimuth or pan angle will subsequently be referred to as the "Pan System", and the other system, designed to measure the elevation or tilt angle, will be referred to as the "Tilt System". However, because the two systems are quite similar the discussion which follows will only specifically describe the operation of both systems where their operation differs.

In the most general terms, the measurement system shown in Figure 2 on page 6 uses two microprocessors to count the pulses generated by the incremental shaft encoders, and to provide output signals to the display devices. The counting function performed by each microprocessor involves determining the direction of rotation and determining whether each count is "valid". Valid counts are encoder pulses which result from the displacement of the camera servo, while invalid counts are a result of the hysteresis in the gear train. The number of valid counts is directly proportional to the angular displacement of the camera axis.

Both of the displays are capable of presenting the position information in two basic forms. In the Count Mode they display the number of pulses that have been detected, and in the Position Mode they display the angle in degrees that the number of pulses represents. A third display mode, which is a combination of the first two, is also available. In the third mode, referred to as the "Blinking Mode", the display will alternately display the count and the angle.

B. SHAFT ENCODER AND LINE DRIVER

Figure 11 shows the basic components of the HEDS-6000 incremental optical shaft encoder. The encoder is approximately 56 mm in diameter and 20 mm deep. The code wheel assemblies for the HEDS-6000 J06 encoders are designed to mount on 0.25 in. shafts. Since the mounting surface shown in Figure 11 is not part of the encoder kit, and did not existed on either of the worm axes, two such surfaces were machined in the

Physics Department Shop and attached to one end of each of the worms. Each surface has a 0.25 in. diameter shaft to which one of the code wheel assemblies is attached. Two sheet metal brackets, also made in the Physics Department Shop, are bolted to the servo frame. The encoder bodies are mounted to these brackets. Figure 12 shows the shaft encoders mounted in the camera servo. [Ref. 9: p.1]

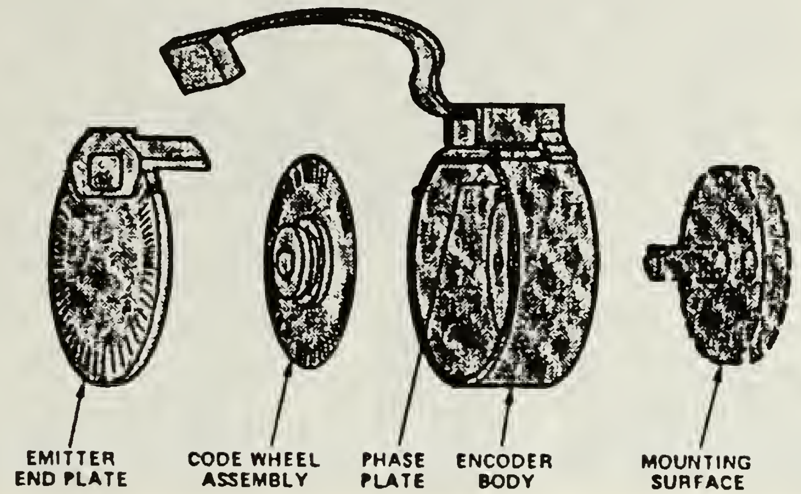


Figure 11. HEDS-6000 Series Encoder Kit: From Ref 9: p.6.

Also seen in Figure 12 is a printed circuit board mounted between the two optical shaft encoders. Each of the encoders is electrically connected to the board via a separate ten wire ribbon cable. The power and the output signals from the shaft encoders are transmitted through these cables. A sketch of the ribbon cable connector and the pinout for the connector are shown in Figure 13. Each connector is attached to a ten pin header on the printed circuit board. Pins 2, 7 and 9 are connected to a +5.0 Vdc power supply external to the camera servo. A description of the power supply is given later in this chapter. Pins 3, 4, 5 and 6 are connected to the power supply ground. The HEDS-6000 does not have an index pulse, therefore pin 10 is not connected.

The remaining two pins on each header connect the output channels of the shaft encoders to two 74S140 line drivers. Each 74S140 is a dual four-input NAND gate 50-Ohm line driver. The line drivers are powered by the same supply as the encoders. They serve as buffers between the encoders and the transmission lines which are used to transmit the encoder signals to the signal conditioner. The line drivers' typical high

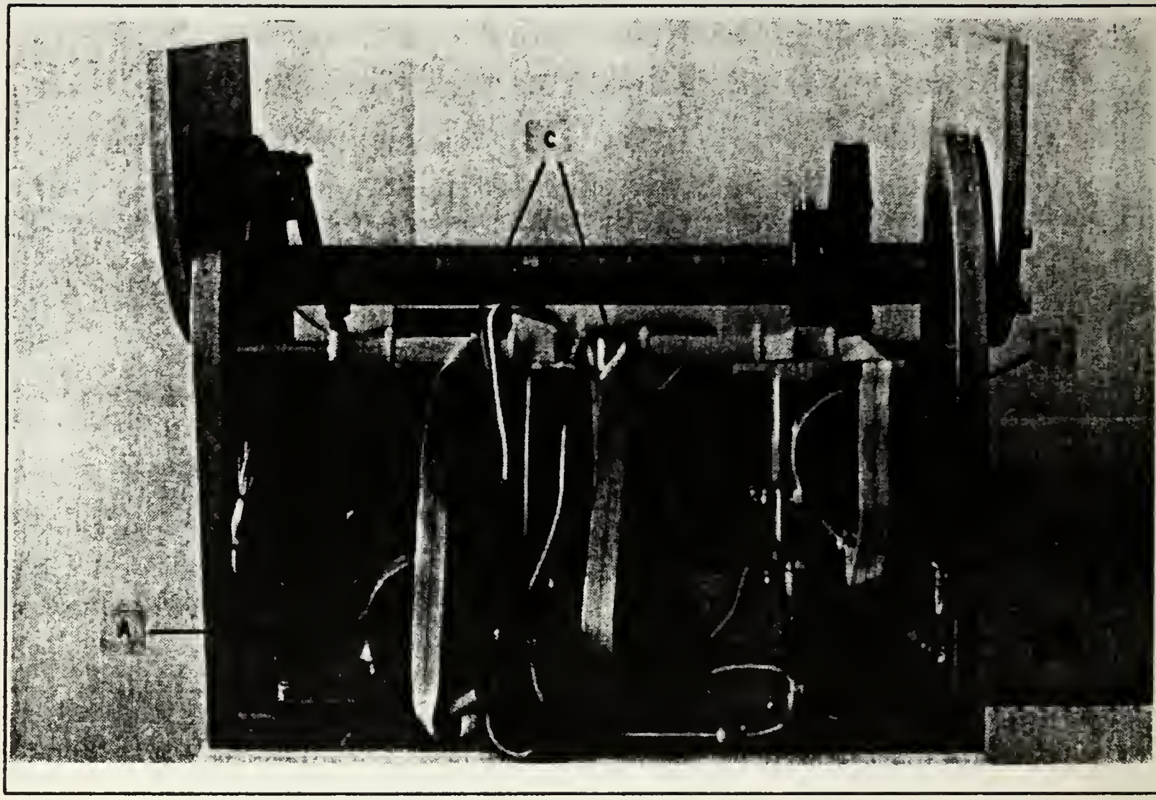


Figure 12. Modified Camera Servo: (a) Optical shaft encoder used to measure Pan axis displacement, (b) Optical shaft encoder used to measure Tilt axis displacement, (c) Ribbon cable, (d) Printed circuit board.

output current is 10 mA and the maximum is 18 mA. Resistance in the transmission line was measured to be approximately 35 Ω, and to be on the safe side a 10 Ω connector loss was assumed. The voltage drop due to an 18 mA current through a 45 Ω resistance is 0.81 V. A "voltage high" signal received at the signal conditioner should therefore be about 4.19 V. This is well above the maximum, positive-going threshold voltage specification of 2.0 V for the 7414 Schmitt triggers, which are used to receive the signals at the signal processor. [Ref. 11: pp. 5-73, 5-74, 6-44]

C. ENCODER-MICROPROCESSOR INTERFACE

The signals transmitted by the two line drivers are Channels A and B of each of the shaft encoders. These signals contain the raw data which the signal processor converts into position information. Three pairs of multiple pin connectors are used in the encoder-microprocessor interface. The pinouts for these connectors are shown in

PINOUT

PIN #	FUNCTION
1	CHANNEL A
2	V_{CC}
3	GROUND
4	N.C. OR GROUND
5	N.C. OR GROUND
6	GROUND
7	V_{CC}
8	CHANNEL B
9	V_{CC}
10	CHANNEL I

Figure 13. Encoder Connector Specifications: From Ref. 9: p. 6.

Figure 14. Each of the four signals is received at the signal processor by a 7414 Schmitt trigger which is used to "clean up" the signal. The Schmitt triggers lower the system's susceptibility to errors caused by slow state transitions and increase the signals' fan out capabilities [Ref. 7: p. 13].

The output of each Schmitt trigger is routed to an input port of the appropriate microprocessor. Each Channel A signal is also the input to an edge detector. The edge detectors each consist of three 7414 inverters, a 74LS86 EXOR gate and a 47 nF capacitor, configured in the manner shown in Figure 15. This configuration causes the interrupt line to go low for approximately 2 μs each time Channel A transitions from low to high or from high to low. Since an oscillator frequency, f_{osc}, of 4.0 MHz is being used, the interrupt pulse width, t_{WL}, must be greater than or equal to 1.25 μs [Ref. 10: p. 3]. The value of the capacitor required to achieve the 2 μs delay was determined experimentally.

D. SWITCHES

The measurement system has 10 switches that allow the operator to control specific functions of the signal processors and the displays. Figure 16 shows the physical location of these switches on the control panel. Switches SW1(P) and SW1(T) control the reset lines to the microprocessors. Switches SW2(P), SW2(T) and SW5 control the display mode. The Function and Set switches; (SW3(P), SW3(T), SW4(P) and SW4(T)) allow the user to change the length of the hysteresis buffer in the microprocessor. The

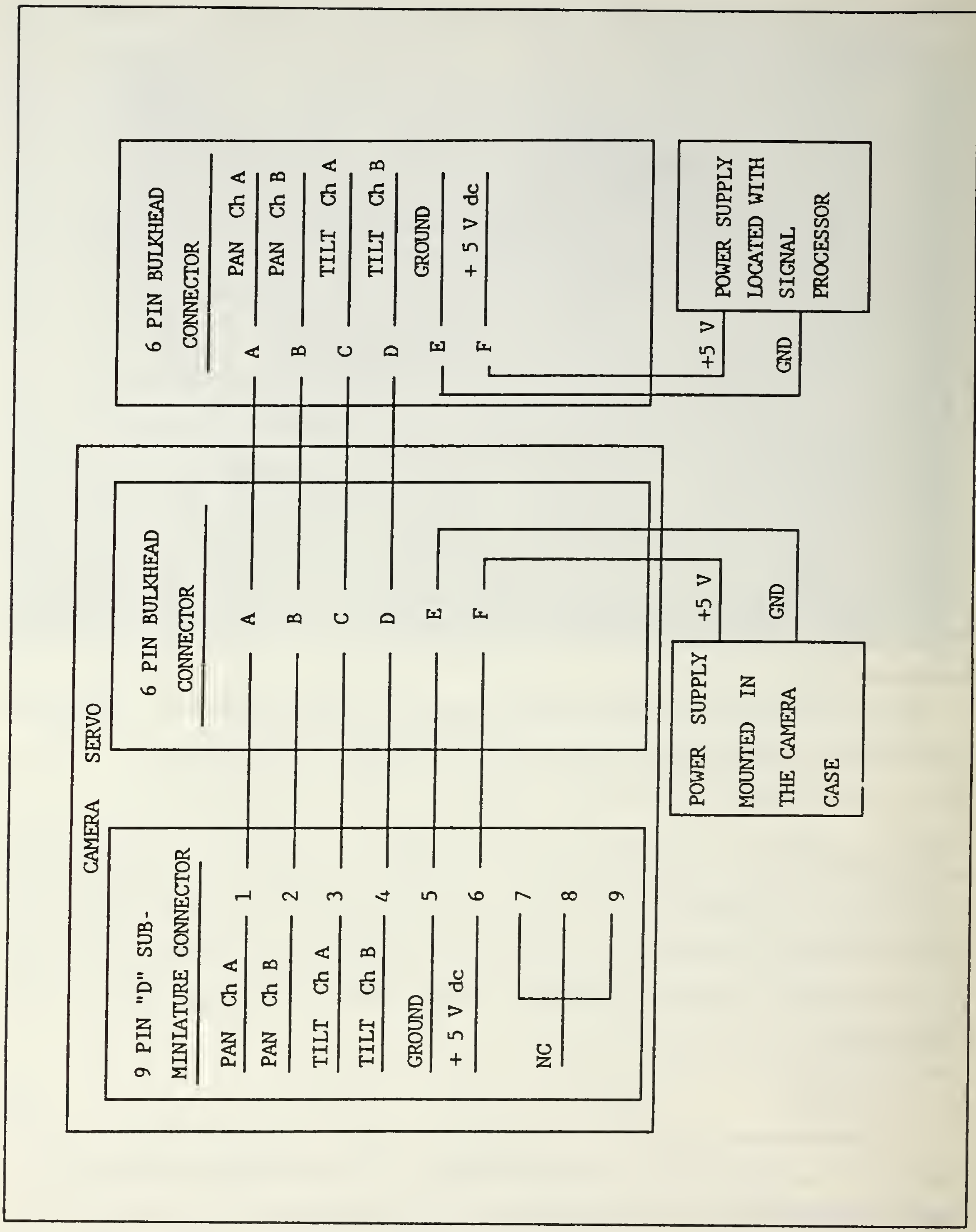


Figure 14. Encoder-Microprocessor Connector Specifications

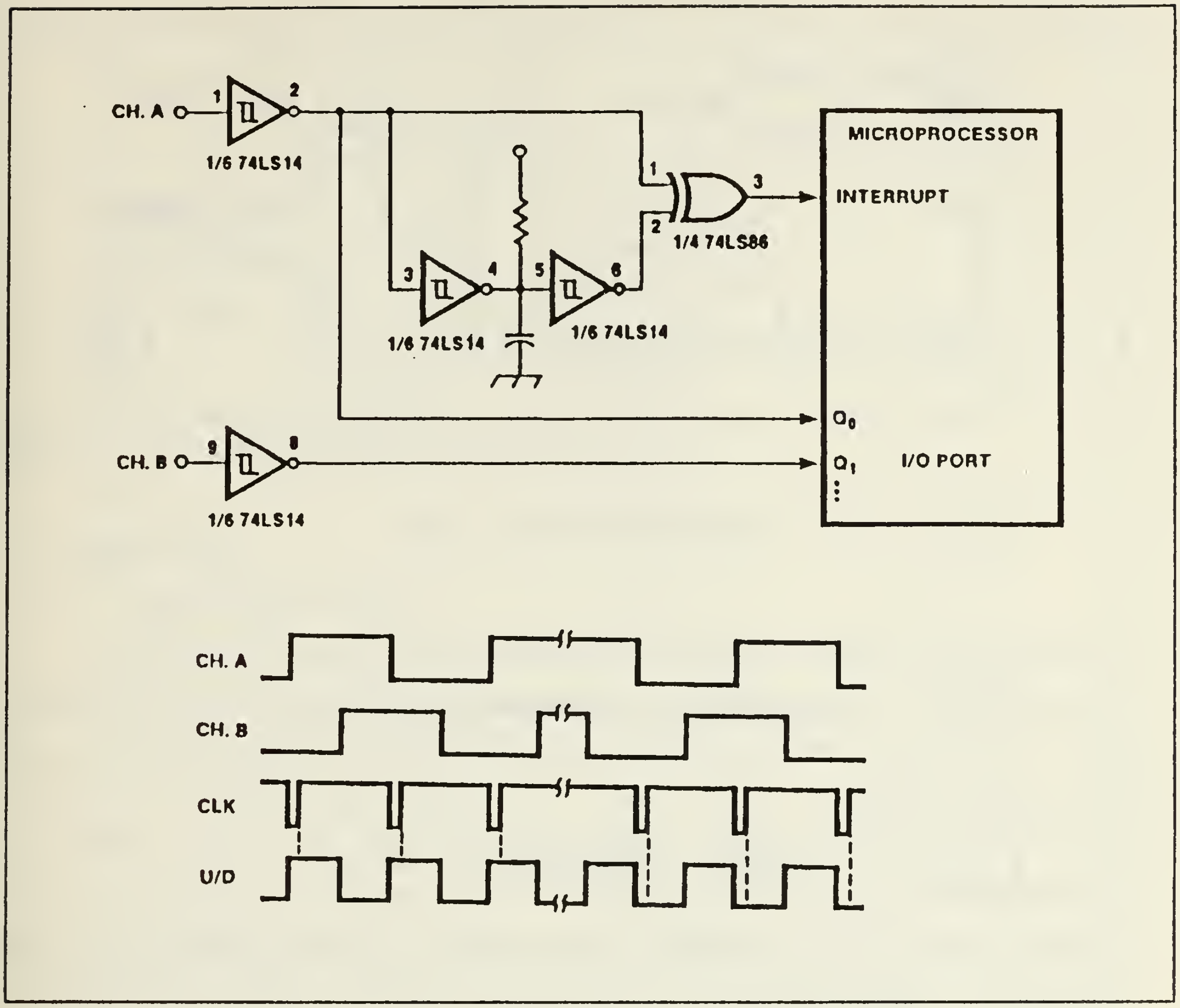


Figure 15. Interrupt Interface: After Ref 7: p. 14.

master power switch is SW6. Table 2 identifies the switches by name, description and function.

Any mechanical switch will "bounce" or "chatter" when it is thrown, and since the operation of the signal processor depends on the number of times that the Display Mode and Set switches change position, these switches had to be "debounced". A very simple but effective way to do this is with an $\overline{RS}$ latch. Switches SW2(P), SW2(T), SW4(P) and SW4(T) are each debounced in this manner. Each latch is made from two 74S00 NAND gates connected in the manner shown in Figure 17. [Refs. 13: pp. 132-135, 12 : pp. 3,4]

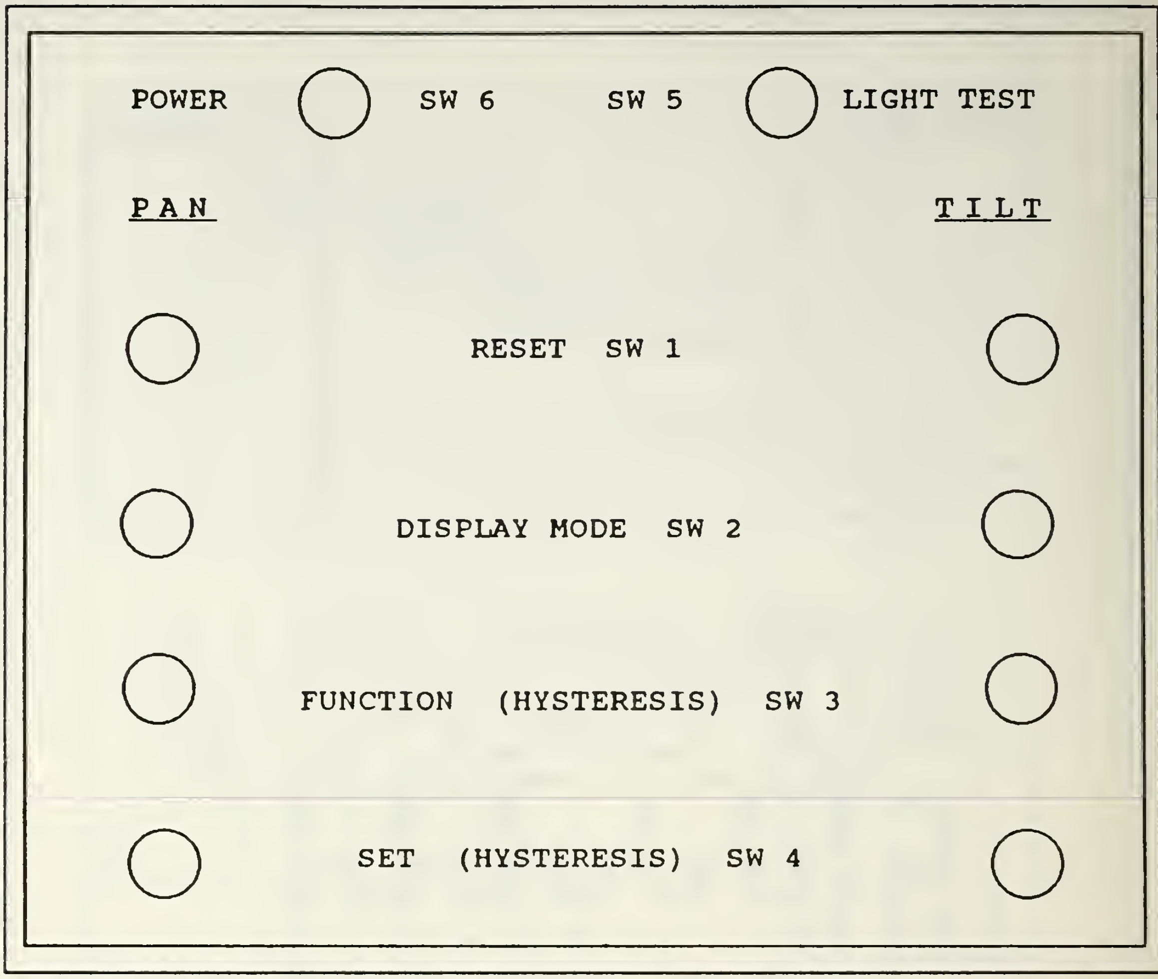


Figure 16. Control Panel

E. MC68705U3

1. General

The two 40 pin MC68705U3 microprocessors (MPU's) are the heart of the measurement system. With the exception of the light test signal, every signal in the system is either part of the input to one of the MPU's or part of their output. The MPU's were programmed using the assembly language syntax, assembler directives and instruction set for the M6805 family of microprocessors which are described in Ref. 14. The Pan and Tilt programs are listed and their operation is described in Appendix D. The pin assignments for the MC68705U3 are shown in Figure 18. Table 3 briefly describes the purpose of each pin and the actual connections for the two MPU's.

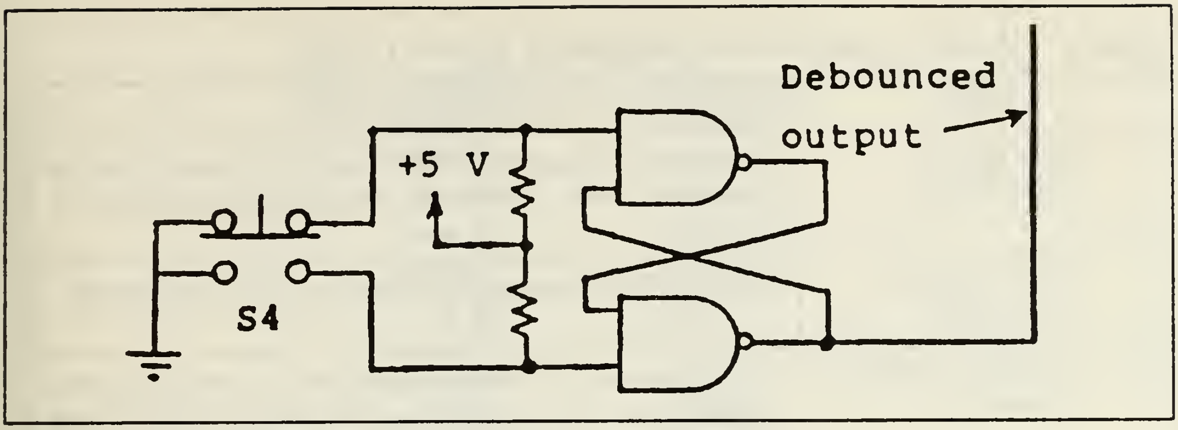


Figure 17. Debouncing circuit: After Ref 12: p. 4.

2. Memory Map

a. Input/Output (I/O)

The memory map for the MC68705U3 is shown in Figure 19. The digits following a "S" are the hexadecimal representation of the address for a specific memory location. The data registers occupy the first four memory locations of each MPU. Thus the information written into the registers at S000, S001 and S002 is written to the output ports A, B and C respectively. Port D, at address S003, is an input only port as indicated in Table 3. In order to determine the state of the input lines, the contents of the register at S003 must be read by the MPU. Registers S004, S005 and S006 are the data direction registers (DDR's) for Ports A, B and C respectively. Because all three ports are used as "output only" ports, in this application, the DDR's are all established as such by an initialization routine performed by the MPU's during their initial power-up and after each external reset. [Ref. 10: pp. 5, 12, 14]

Pin 18 of the MPU can be used as either a general purpose input line or as an interrupt line. The primary interrupt line on each MPU is used to signal the occurrence of a state transition on Channel A. Pin 18 is used as a second interrupt line to signal a display mode change request from the operator. The Miscellaneous Register (MR) at address S0A is used to control the operation of the second interrupt line ($\overline{\text{INT2}}$). In order to establish pin 18 as an interrupt line, bit 6 of the MR is cleared by the Initialization Routine. The $\overline{\text{INT2}}$ Interrupt Request Bit, bit 7 of the MR, is cleared by default upon reset. It is set when a falling edge is detected on the Display Mode line which is connected to pin 18. When this occurs and bit 6 of the MR is cleared, an interrupt request is generated. This interrupt request causes the display mode to change.

Table 2. SIGNAL PROCESSOR AND DISPLAY SWITCHES

NAME	DESCRIPTION AND FUNCTION
PAN RESET (SW1(P))	Momentary action push button switch: Resets the Pan Microprocessor. Causes the Pan Display to be reset to zero.
TILT RESET (SW1(T))	Same as SW1(P) except it affects the Tilt System only.
PAN DISPLAY MODE (SW2(P))	Single pole double throw toggle switch: Each time the switch position is changed the Pan Display toggles from Count mode, to Position Mode, to Blinking Mode, to Count Mode, etc..
TILT DISPLAY MODE (SW2(T))	Same as SW2(P) except it affects the Tilt Display only.
FUNCTION (HYSTERESIS) (SW3(P))	Single pole double throw switch: When closed, causes the "Function" line of the Pan Microprocessor to go low and causes the size of the hysteresis buffer to be displayed on the Pan Display. Enables SW4(P).
FUNCTION (HYSTERESIS) (SW3(T))	Same as SW3(P) except it affects the Tilt System only.
SET HYSTERESIS (SW4(P))	Single pole double throw switch: Inoperable unless SW3(P) is closed. If SW3(P) is closed, each time the position of SW4(P) is changed the length of the hysteresis buffer is incremented by one. Maximum buffer length is 25. Toggling SW4(P) when the buffer length is 25 will cause the buffer length to be reset to zero.
SET HYSTERESIS (SW4(T))	Same as SW4(P) except it affects the Tilt Hysteresis buffer.
LIGHT TEST (SW5)	Single pole single throw switch: When closed, lines 1, 2, 7, 8, 10, 11 and 13 on each of the LED displays will go low. Unless an element is burned out, every digit in both displays should be an eight.
POWER (SW6)	Single pole single throw switch: When closed, applies +5.0 V dc power to the signal processors and the displays.

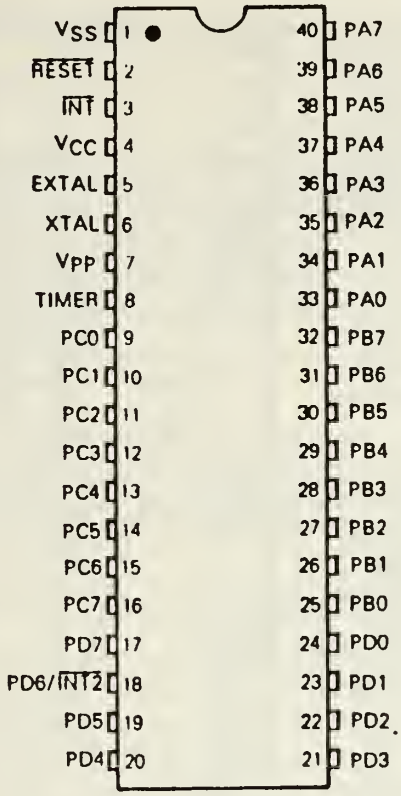


Figure 18. MC68705U3 Pin assignments: From Ref. 10: p. 1.

Once bit 7 has been set by an interrupt, it must be cleared by software to avoid repeated and unwanted interrupts from occurring. This task is performed by the Mode Change Routine in each EPROM. [Ref. 10: pp. 1, 10, 13, 15]

b. Timer

The operator can cause either or both of the displays to "blink" by using the Display Mode Switches, SW2(P) and SW2(T). When one of the systems has its display in the Blinking Mode, the associated MPU uses its timer to generate a timer interrupt request every second. The interrupt request causes the MPU to execute the Mode Change Routine. A block diagram of the timer is shown in Figure 20. The timer consists of an eight-bit counter which is decremented toward zero by the f_{CIN} input. When the counter reaches zero, it sets the Timer Interrupt Request Bit (TIR) of the Timer Control Register (TCR), and a timer interrupt request is generated unless the

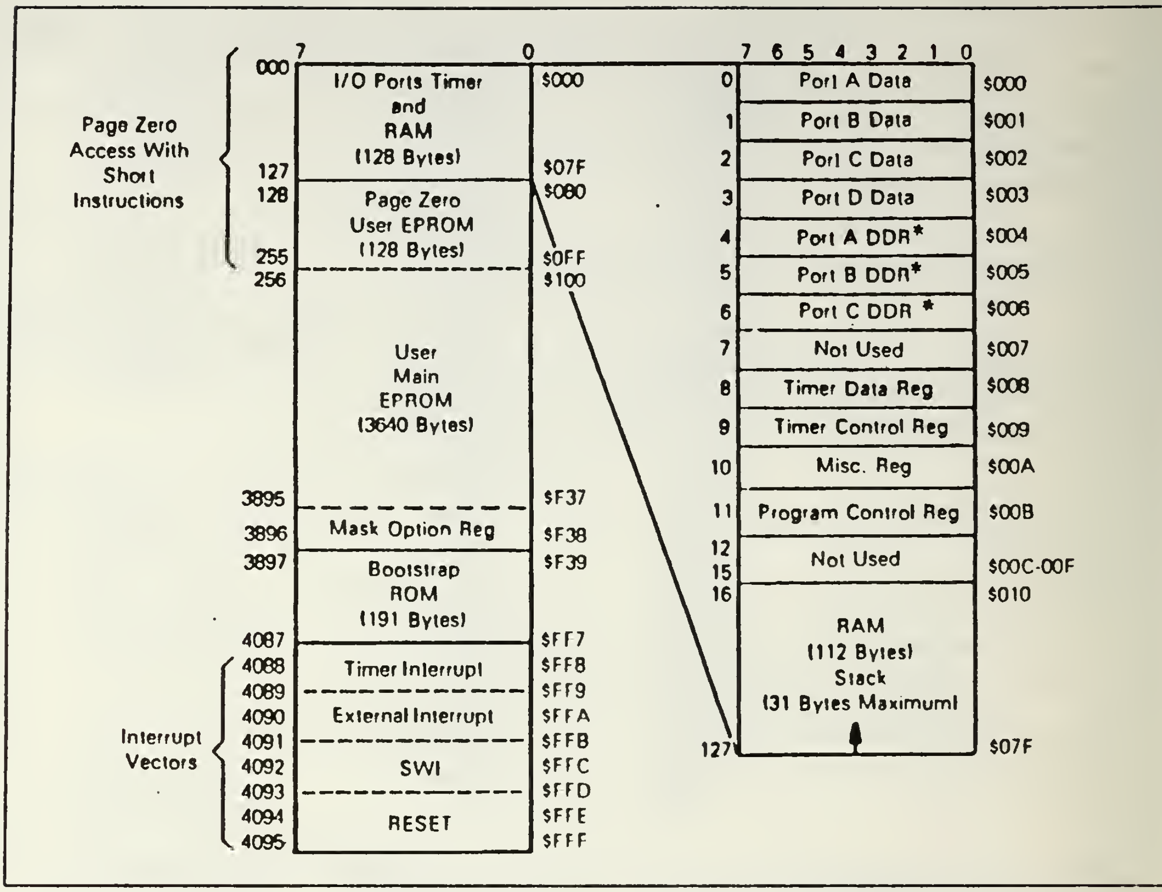


Figure 19. MC68705U3 Memory Configuration: From Ref. 10: p. 5.

Timer Interrupt Mask Bit (TIM) of the TCR is set. A brief description of each of the timer registers and their configuration follows.

(1) Timer Data Register (TDR). The TDR is the eight-bit counter which sets the TIR bit of the TCR when it decrements to zero.

(2) Timer Control Register. The contents of the TCR determine the general operation of the timer.

- Bit 7, Timer Interrupt Request (TIR), signals a TDR underflow when it is set and will cause a timer interrupt request if the TIM bit of the TCR is clear. The TIR is cleared by the MPU reset or by program control.
- Bit 6, Timer Interrupt Mask (TIM), inhibits a timer interrupt request when it is set. It is set by external reset or program control to inhibit the Blinking Mode, and is cleared by software when the Blinking Mode is requested by the operator.
- Bit 5, External or Internal Clock Select (TIN), is used to select the timer clock source. Since the internal clock is used in this application, the TIN bits of both

Table 3. MPU CONNECTIONS

Pin	Name	Description
1	V_{SS}	Ground
2	$\overline{\text{RESET}}$	When $\overline{\text{RESET}}$ is pulled low program execution halts, all variables are reinitialized and the Pan display is set to zero. SW1(P) controls the RESET line on the Pan MPU.
3	$\overline{\text{INT}}$	Allows asynchronous interruption of the processor. When $\overline{\text{INT}}$ is pulled low by the Count Edge Detector the MPU executes the "Count Routine".
4	V_{CC}	+5 V dc power connection.
5	EXTAL	External clock input. Connected to a 4.0 MHz external clock which provides the MPU system clock.
6	XTAL	Crystal clock input. Connected to ground since an external clock is used.
7	V_{PP}	Programming voltage pin. Connected to V_{CC} for normal operation.
8	Timer	External timer control input. Connected to V_{CC} since the internal timer is used.
	Port C	General Purpose I/O lines.
9	PC0	The two least significant digits in the display are represented in binary coded decimal (BCD) by these eight lines.
10	PC1	
11	PC2	
12	PC3	
13	PC4	
14	PC5	
15	PC6	
16	PC7	
	Port D	General Purpose input lines.
17	PD7	PD7 is the Channel A input to the MPU.
18	PD6/$\overline{\text{INT2}}$	PD6 is used as a second interrupt line. When PD6 goes low the MPU changes display modes.
19	PD5	PD5 is the Channel B input into the MPU.
20	PD4	PD4 is the Function input into the MPU.
21	PD3	PD3 is the Set input into the MPU.
22	PD2	PD2-PD0 are not used and are tied to ground.
23	PD1	
24	PD0	

Table 4. MPU CONNECTIONS (CONT'D.)

Pin	Name	Description
	Port B	General Purpose I/O lines (LED compatible).
25	PB0	The most significant digit is represented in BCD by PB0-PB3 except on the Tilt MPU where these lines are connected to ground.
26	PB1	
27	PB2	PB4 determines which digits in the display are blanked.
28	PB3	PB5 is not used. Connected to ground.
29	PB4	PB6 determines the presence or absence of the display minus sign.
30	PB5	PB7 determines the presence or absence of the display decimal point.
31	PB6	
32	PB7	
	Port A	General Purpose I/O lines.
33	PA0	The third and fourth least significant digits are represented in BCD by these eight lines.
34	PA1	
35	PA2	
36	PA3	
37	PA4	
38	PA5	
39	PA6	
40	PA7	

MPU's are always cleared. For the same reason the Timer pins are connected to V_{CC} (see Table 3).

- Bit 4, External Enable (TEE), is not used by the measurement system. By keeping the TEE clear at all times, the 68705's internal timer is used exclusively.
- Bit 3, Prescaler Clear (PSC), is not used in this application; always cleared.
- Bits 2-0, Prescaler Select (PS2, PS1 and PS0), are always set during program execution. This causes the internal timer signal frequency to be divided by 128.

(3) Mask Option Register (MOR). Unlike the TDR and TCR the MOR is not software programmable; instead, it is implemented in EPROM.

- Bit 7, the Clock bit, is cleared to allow operation of the external 4.0 MHz clock.
- The Timer Option bit (TOPT), bit 6, is also cleared in this application. This permits the TCR to be software programmable.
- Bit 5 is cleared to permit the use of the internal clock with the timer.
- Bits 4 and 3 are not used.

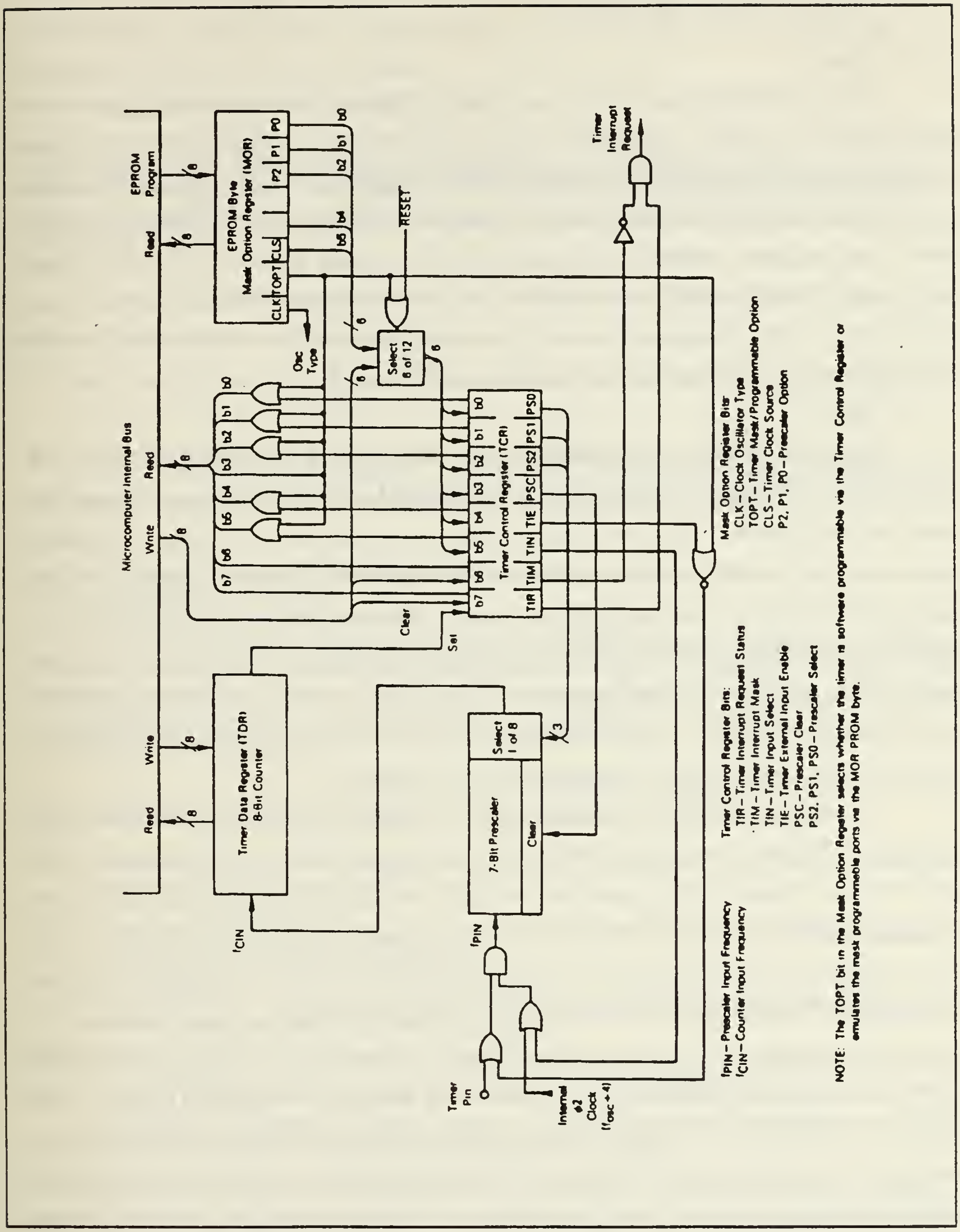


Figure 20. MC68705U3 Timer Functional Block Diagram.: From Ref. 10: p. 8.

- Bits 2-0 are all set and serve the same function as PS2, PS1 and PS0 bits of the TCR. [Ref. 10: pp. 6-8, 13-15]

3. RAM

The MC68705U3 has 112 bytes of RAM. The 112 bytes includes 31 bytes that can be used for the stack. Use of the stack is quite limited. During interrupts it is used to save the contents of the CPU registers and the program counter. During subroutine calls only the program counter is saved. The user's program has no other access to the stack. The programs written for each of the MPU's require less than 25% of the available RAM. The Pan MPU uses 27 of the 112 available bytes and the Tilt MPU uses only 22 bytes. The programs listed in Appendix D explain the function and give the location in memory for each of the variables. [Ref 10: p. 5]

4. ROM

The 3776 bytes of user EPROM in the MC68705U3 are divided into three separate blocks in the memory. Page Zero User EPROM is the ROM located between address $080 and $0FF. Because these addresses are only one byte long, instructions located in Page Zero ROM can be referenced with addressing modes not permitted with instructions located in other parts of the memory. Between address $100 and $F37 is the User Main EPROM. This portion of the memory in each MPU contains the vast majority of the signal conditioning programs. Located in another portion of the EPROM are the Interrupt Vectors. In each of these locations is the address of the first instruction the MPU is to execute when a particular interrupt occurs.

As with the RAM only a fraction of the available EPROM has been used in this application. The Pan MPU uses 899 bytes of the 3776 available and the Tilt MPU uses only 767 bytes. Since both programs are so small, one could reasonably ask why the two programs were not both put in one MPU. The primary problem with this idea is that each microprocessor can perform only one operation at a time. As indicated at the end of Chapter II, if the camera servo is rotating about its vertical axis at its maximum velocity of 1 rpm, the Pan signal conditioner must be capable of counting and displaying 51,200 counts per minute. Using a 4.0 MHz clock this allows the MPU 1172μs to count each pulse. Similarly the Tilt MPU has 1758μs to count each pulse when the camera is rotating at its maximum velocity about the horizontal axis. Assuming that the camera is rotating at its maximum velocity on both axes at the same time, and one MPU is being used to count the pulses from both encoders, the MPU needs to count 76,800 pulses per minute, which only allows 781.3 μs per pulse. The Pan MPU currently requires a max-

imum of 1032 instruction cycles or 1032μs to count a single pulse, and the maximum execution time for a single pulse on the Tilt axis is 825μs. Thus, a single 68705 lacks the computational speed required to ensure that no counts would be missed if it was used to process the data from both encoders.

5. Central Processing Unit (CPU)

> The CPU of the M6805 Family is implemented independently from the I/O or memory configuration. Consequently it can be treated as an independent central processor communicating with I/O and memory via internal address, data and control buses. [Ref 10: p. 6]

The CPU has five registers that are available for use by the operator. The function of each of these is described below.

- The Accumulator (A) is a general purpose data register used for arithmetic calculation and data manipulation.
- The Index Register (X) can be used as a second accumulator but is generally used for the indexed addressing mode. In the indexed addressing mode an effective address is created by adding the contents of X to a number provided by the instruction.
- The Program Counter (PC) contains the memory address of the next instruction to be executed by the MPU.
- The five bits of the Condition Code Register (CCR) keep information concerning the results of the last instruction executed by the MPU. Reference 14 gives a detailed description of each of the instructions in the M6805 Family Instruction Set and explains the effect of each instruction on the CCR. A brief description of each bit in the CCR follows.
    - The Carry (C) bit is set if a carry or a borrow was generated by the last arithmetic instruction. The state of the C bit can be software controlled.
    - The Zero (Z) bit is set if the result of the last arithmetic, logic or data manipulation instruction was zero.
    - The Negative (N) bit is set if bit seven of the result of the last arithmetic, logic, or data manipulation instruction is set.
    - The Half Carry (H) bit is set if an ADD or an ADC instruction causes a carry to occur between bits 3 and 4 of the result.
    - The Interrupt Mask (I) bit is set when an external interrupt ($\overline{\text{INT}}$) occurs. If another interrupt occurs (e.g. Timer Interrupt or $\overline{\text{INT2}}$) when the I bit is set, the second interrupt is latched so that it can be processed as soon as the I bit is cleared. The I bit can be set or cleared by software.
- The contents of the Stack Pointer (SP) are the address of the next available location on the stack. As previously discussed, the stack is only used to keep track of the PC during subroutine branches, and all of the CPU registers during an interrupt. [Refs. 10: p. 6, 14 : pp. 14-15]

6. Input

Each MPU uses six input lines. Two of these lines, $\overline{INT}$ and $\overline{INT2}$, are interrupt lines that detect a negative-going edge on their respective lines. The other four lines are general purpose input lines on Port D. All of the pins on Port D are TTL compatible which made the hardware design relatively straightforward. The electrical characteristics for the input pins are listed on p. 2 of Ref. 10.

The general operation of the two interrupt lines is described in Table 3 on page 39. Once they are understood, interrupts are a simple yet powerful tool. Only three of the four interrupts available on the MC68705U3 are used by the Pan and Tilt programs. The software interrupt is not used. When the MPU is interrupted, current program execution is halted, the contents of the CPU registers are placed on the stack, and the MPU fetches the contents of the appropriate interrupt vector from memory. After the interrupt vector has been fetched, the PC is moved to that address and execution of the interrupt routine begins. There is no ambiguity when an external interrupt occurs since there is a dedicated interrupt vector in memory. The timer interrupt and $\overline{INT}$ however share the Timer Interrupt Vector. When one of these interrupts occurs, the interrupt routine must determine the source of the interrupt by checking the TIR bit of the TCR and bit 7 of the MR to determine the source of the interrupt [Ref. 10: p. 11]. Normal program execution resumes at the point at which the interrupt occurred when the interrupt routine executes a return from interrupt (RTI) instruction.

The Function and Set lines on pins 20 and 21 are connected to the Function and Set switches. The operation of these switches is described in Table 2 on page 36. The remaining two input lines to each MPU are Channels A and B from the respective shaft encoders. The MPU programs use the information from these two inputs to determine the direction of rotation and to identify repeated oscillations about a single transition.

7. Output

Each MPU is designed to provide position information at its output in two basic forms. On the Pan axis, in the Count Mode a number between -51,200 and +51,200 constitutes the output while in the Position Mode the output is an angle between 0° and 360°. A five digit display with a minus sign is sufficient for the count display. Using a five digit display with a decimal point in the Position Mode permits the angle to be displayed to the nearest hundredth of a degree. This resolution is not quite as good as the resolution of the shaft encoders ($\pm 0.007°$); however, final testing of the measurement system revealed that resolution is actually limited to about $\pm 0.02°$ on the Pan axis and

about $\pm 0.14°$ on the Tilt axis. The five digit display is therefore completely adequate for this system.

The Pan MPU uses 23 of its 24 output pins to represent the five digits, a minus sign and a decimal point. Each of the five digits is available in BCD form on four output pins of the MPU. The five digits are referred to as Digit 1, Digit 2, etc., with Digit 1 being the least significant digit and Digit 5 being the most significant digit. Port A has as its output the BCD representation of Digit 3 and Digit 4. Digit 1 and Digit 2 are represented by the output of Port C. The low four bits of Port B contain the BCD representation of Digit 5. These 20 output lines are the input to five 74LS47, BCD/7-Segment Decoder/Drivers, which decode the BCD signals and drive the common anode LED indicators. The output from Pin 29, PB4, is one input to a 74LS32 OR gate, the output of which is used to blank leading zeros out of the display. Pin 30 is not used and is tied to ground. The remaining two output pins drive two LED segments in the display. The signal on pin 31 turns the minus sign off and on, and the signal on pin 32 determines whether the decimal point is displayed.

The electrical characteristics of the I/O Ports are given on p. 4 of Ref. 10. The output characteristics of Ports A, B and C are compatible with the input characteristics of the 74LS47 and the 74LS32 given on pp. 4-59 and 4-48 of Ref. 11. The pins on Port B are capable of sinking 10 mA when Port B is configured as an output port. A 220 Ω resistor placed in series with each of the display segments limits the current to approximately 9 mA and permits the MPU to drive the decimal point and minus sign directly.

One consideration in the design of this system was to provide a system capable of being readily expanded to meet changing needs. To this end, in addition to being connected to the LED display devices via the 74LS47's, the BCD data lines are also connected to a header on each of the MPU circuit boards. If, at a later date, the position information needs to be used in another system, a jumper connected to each of the headers could provide the information with little or no modification.

The Pan and Tilt signal processing subsystems are virtually identical in the hardware used to implement them. The only difference is that the Pan system has a five digit display, and the Tilt system needs only four digits to display its position information. Consequently, the Tilt system does not use Digit 5, and pins 25-29 are tied to ground.

F. DISPLAY

Each digit represented in BCD at the output of the MPU is decoded by a 74LS47 BCD/7-Segment Decoder/Driver. The decoding devices each convert a four bit BCD representation of a number into seven signals that each drive a separate segment of a common anode, seven segment, LED display. The 74LS47 is capable of sinking 24 mA from each of the LED segments. Without a current limiting resistor between each of the output pins on the 7447 and the corresponding pin on the display element however, this maximum current is exceeded. When this happens the LED's have a very short life, the 7447 overheats and the system fails to function properly. The addition of a 220 Ω resistor in each branch limits the current to about 9 mA per segment, and permits trouble-free operation.

Three of the output pins on each MPU are not used as inputs to the 7447's. As discussed in the previous section, the Decimal and Minus lines each drive individual LED segments directly. The third line, also mentioned briefly in the preceding section, is used with the Blanking In/Ribbon Blanking Out (BI/RBO) signal from Digit 4's 7447 to determine the Ribbon Blanking In (RBI) signal into the 7447 which drives the display for Digit 3.

The term "blanking" simply means removing the leading zeros from the display. The two display modes available from the MPU's have different blanking requirements. In the Position Mode the three least significant digits are not blanked, while in the Count Mode, all but the least significant digit are blanked. The RBI and BI/RBO pins on the 7447's, the Blank line out of each MPU and the OR gates, connected as shown in the schematics in Appendix A, provide this capability.

The Light Test (LT) pin on each 7447 is connected to SW5. When the switch is closed, the Light Test line goes low and each of the output lines on each of the 7447's also goes low, thus sinking current from all of the LED segments simultaneously. This feature allows the operator to check for inoperable display segments.

G. POWER SUPPLIES

The two power supplies shown in Figure 2 on page 6 are each +5.0 Vdc supplies. The power supply which provides power to the shaft encoders and the line drivers is physically mounted in the camera housing. It was built by modifying the +12 Vdc auto iris power supply. This was accomplished using an LM7805 Voltage Regulator in the manner shown in Figure 8 of Appendix A. The auto iris requires only 100 mA at +12 Vdc for correct operation, and the LM7812 Voltage Regulator has an available

output current of 1.0 A [Refs. 15, 16]. The remaining 900 mA is available to the LM7805 to power the encoders and the line drivers. Reference 9 lists the maximum power requirement for the HEDS-600 as 40 mA at +5 Vdc, and Ref. 11 specifies the maximum power requirement for a 74S140 is 1 mA at +5 Vdc. Thus, the 84 mA requirement for the two encoders and four line drivers is well within the capabilities of the modified power supply.

The second power supply is capable of providing 6.0 A at +5 Vdc which is more than adequate to provide the 1.4 A needed by the signal processors and the display devices. The power supply also has 12 Vdc and -5 Vdc ports. To preclude the potentially disastrous results which might occur if the power supply were incorrectly connected to the signal processor/display devices, the circuitry shown in Figure 21 was included on each MPU and display printed circuit board.

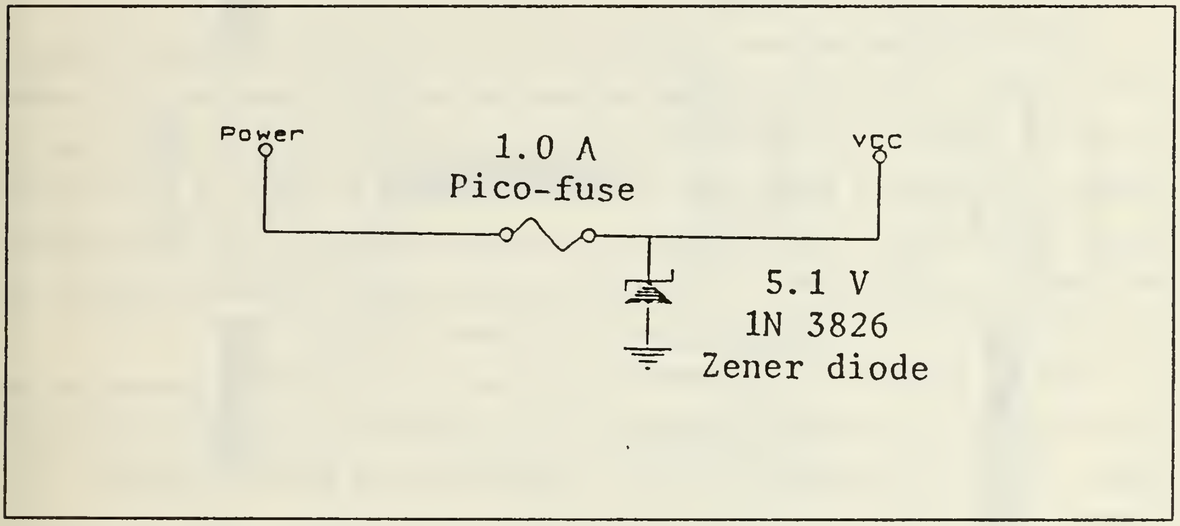


Figure 21. Reverse/Over-voltage Protection Circuit

IV. CALIBRATION , TESTING AND IMPLEMENTATION

A. GENERAL

Once the basic system design had been completed, and the MPU programs had been written, a prototype system was constructed. The prototype system might also be called the development model, since it was not only used to test the design , but was also used to calibrate the MPU programs. A block diagram of the prototype system is shown in Figure 22. The M68705EVM Evaluation Module (subsequently referred to as the EVM) provided the capability to debug and evaluate the MC68705U3-based signal processing subsystem. Operation of the signal processing MPU was performed by an MC68705U3 resident on the EVM.

The prototype system provided considerable flexibility in the testing and calibration of the system. The assembly language programs for the MPU's were written and edited on the PC. They were then assembled and linked using the 2500 A.D. 6805 Cross Assembler and 2500 A.D. Linker [Ref. 17: pp. (1-1)-(2-38)]. The result, a Motorola S19 output file (see [Ref. 17: pp. (A-1)-(A-4)]), was then down-loaded to the EVM using the file transfer program, Kermit. Downloading procedures are detailed in [Ref. 18: pp. (3-10)-(3-25),(3-37)]. The PC-EVM interface is shown in Figure 23.

After the program had been down-loaded into the MC68705U3 resident on the EVM, data entry and program debugging were controlled via the CRT monitor keyboard. The CRT-EVM interconnection is shown in Figure 24 and the monitor commands are described in [Ref. 18: pp. (3-8)-(3-25)].

The remainder of the signal processing functions were realized using hardware external to the EVM. These functions included edge detection of the output signals from the shaft encoders, decoding the output of the MPU, and generating the signals to drive the display devices. This portion of the prototype, referred to by [Ref. 18] as the "target system", was built on breadboards and is represented by the block in the center of Figure 22. The target system was connected to the MCU via a 40-pin jumper header, J1, on the EVM. The pinout for J1 is shown in Figure 25. The labels in Figure 25 refer to the labels used in the schematic diagrams which are shown in Appendix A.

B. CALIBRATION

Once the MPU programs were capable of counting the pulses generated by the shaft encoders, the programs needed to be "calibrated". This calibration procedure required

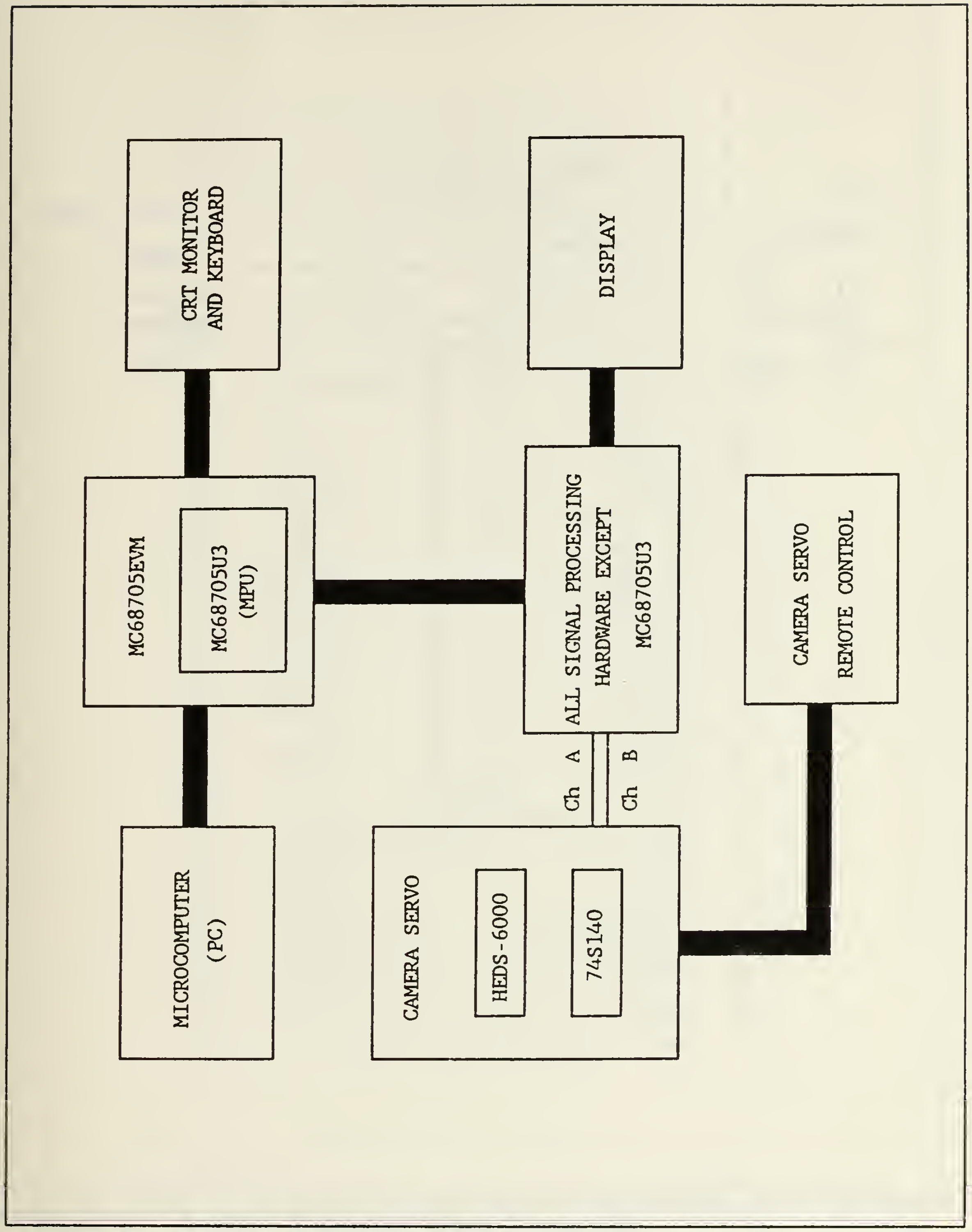


Figure 22. Prototype/Development Model

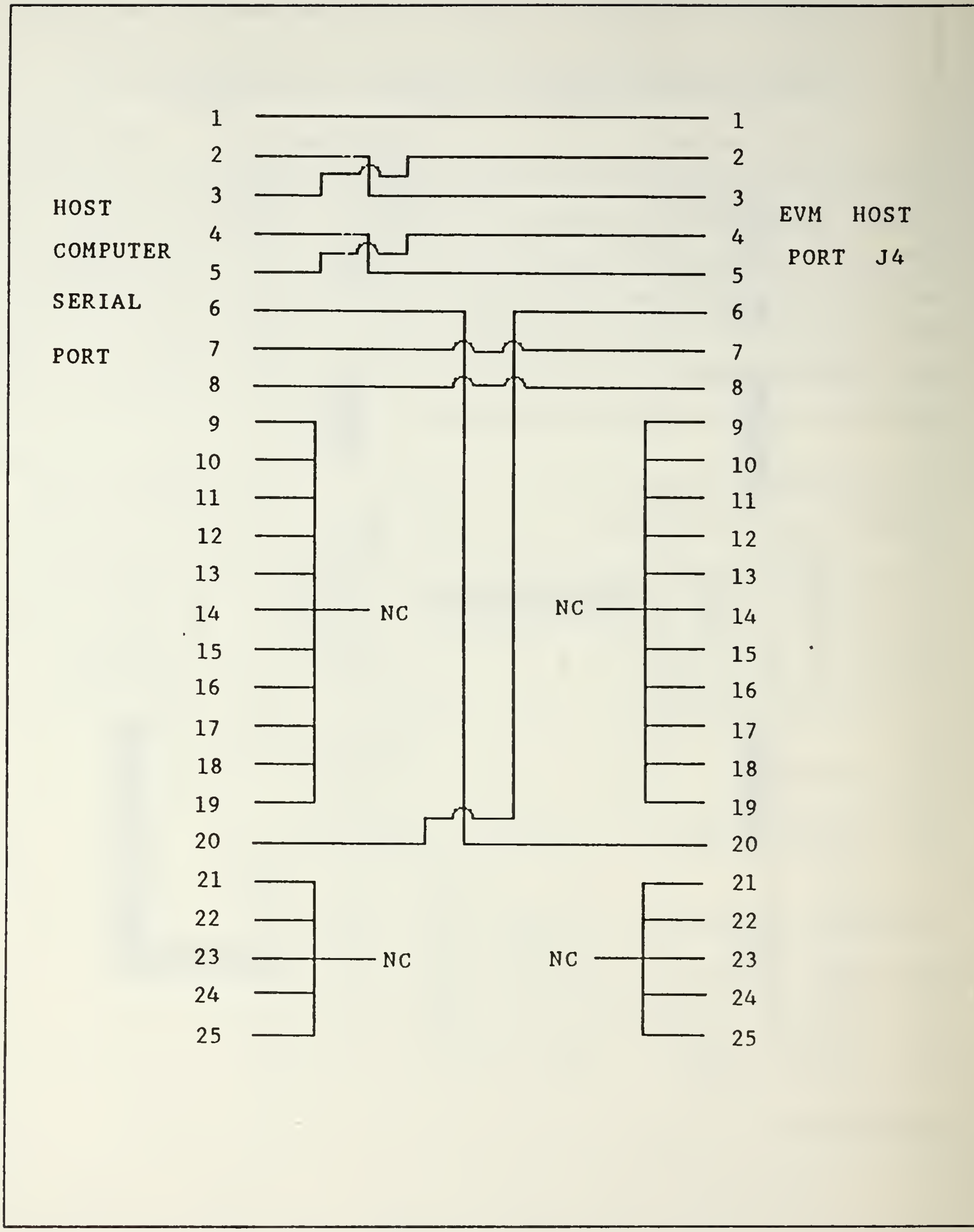


Figure 23. Host Computer - Evaluation Module Connections

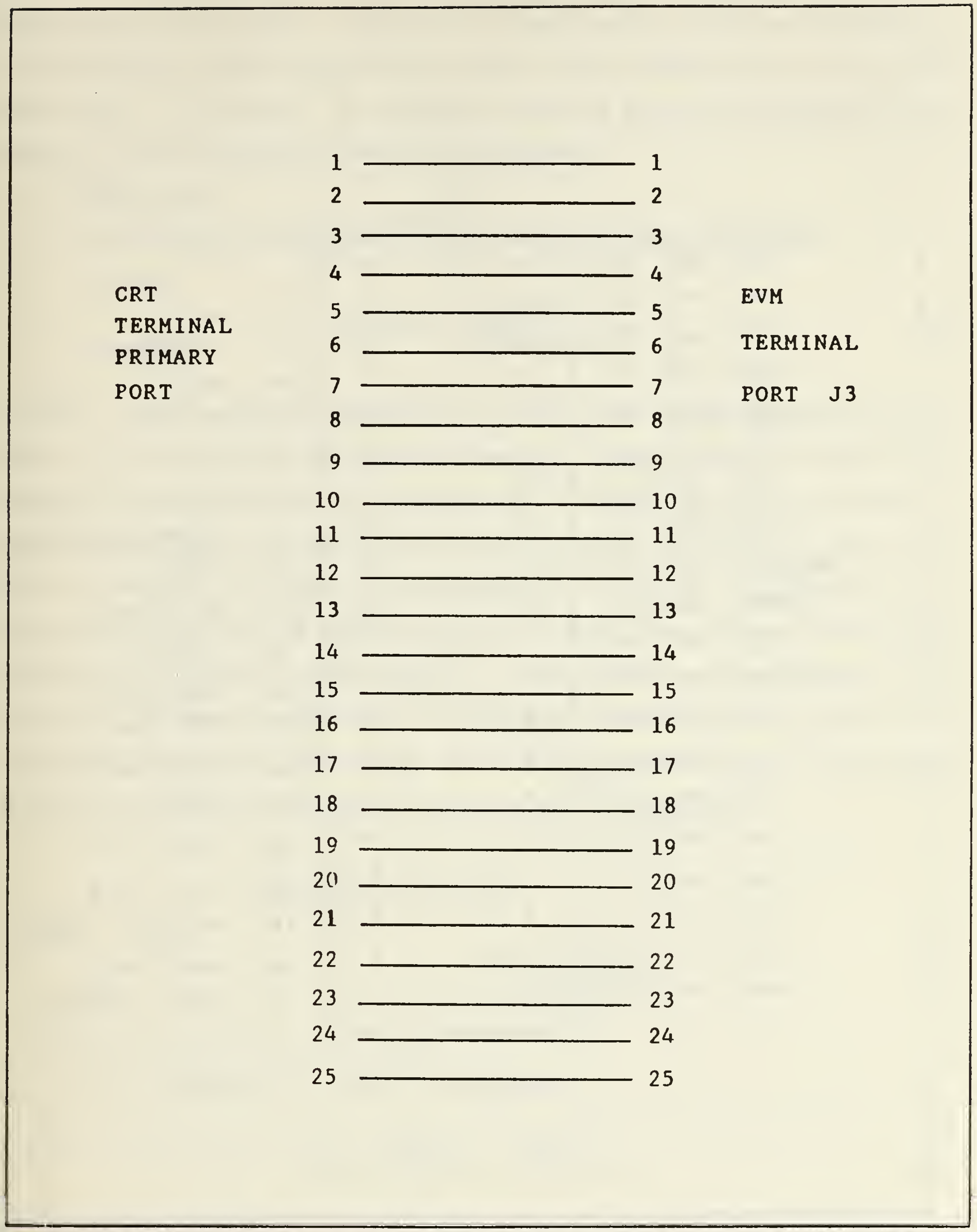


Figure 24. Monitor - Evaluation Module Connections

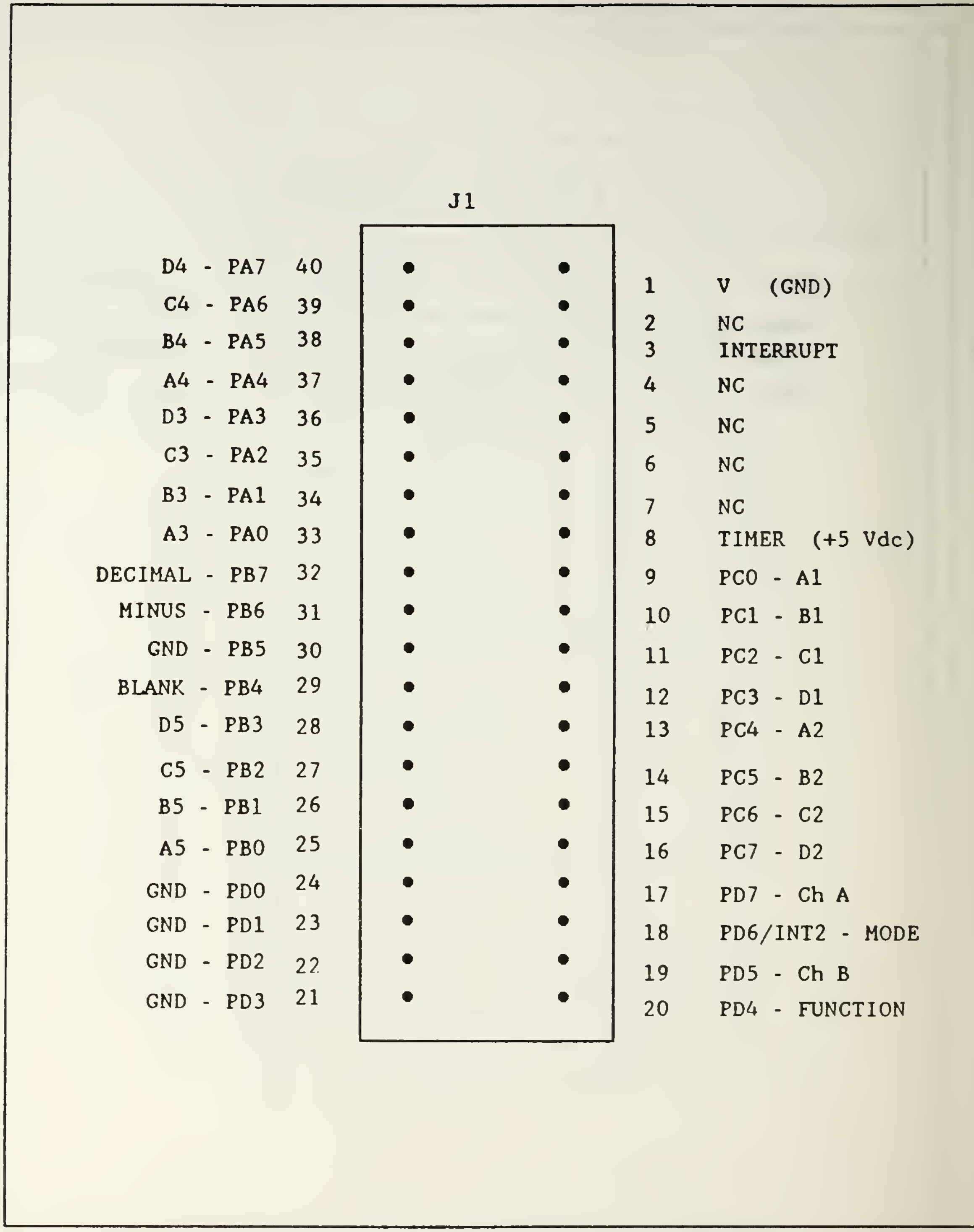


Figure 25. Evaluation Module - Signal Processor Connections

determining the angular distance through which the camera rotated between successive pulses from the shaft encoder. This number is a scale factor, which, when multiplied by the total number of pulses from the shaft encoder, yields a number equal to the angular displacement of the camera. The calibration procedure also involved determining the amount of hysteresis present in each of the gear trains.

1. Scale Factor

To determine the scale factor (SF) the simple geometric relationship

$$\theta = \tan^{-1}\left(\frac{\text{opposite}}{\text{adjacent}}\right) \tag{12}$$

was used. Using a small laser attached to the camera servo, and the geometry shown in Figure 26, the SF could be experimentally determined. As the camera servo was rotated through an angle, θ, the MPU was used to count the output pulses from the shaft encoder. The laser beam was projected on a vertical surface at a distance, a, away from the axis of rotation. The beam of the laser spread to a diameter of approximately 0.4 in. over a distance of 30 ft. A template with a 0.4 in. diameter aperture was used to mark the location of the "spots" on the distant wall. The distance between the spots, l, was measured by selecting one edge of one of the marks and measuring the distance to the corresponding edge of the distant mark. Then, having determined l and a and reading the count, C, from the display, the SF could then be determined from

$$\begin{aligned} \text{SF(degrees/Pulse)} &= \frac{\theta}{\text{C}} \\ &= \frac{\tan^{-1}\left(\dfrac{l(\text{in})}{a(\text{in})}\right)}{\text{C}} \quad . \end{aligned} \tag{13}$$

Using Equation (13) to simplify the expression,

$$\text{d(SF)} = \frac{\delta(\text{SF})}{\delta l}\,\text{d}l + \frac{\delta(\text{SF})}{\delta a}\,\text{d}a \tag{14}$$

yields

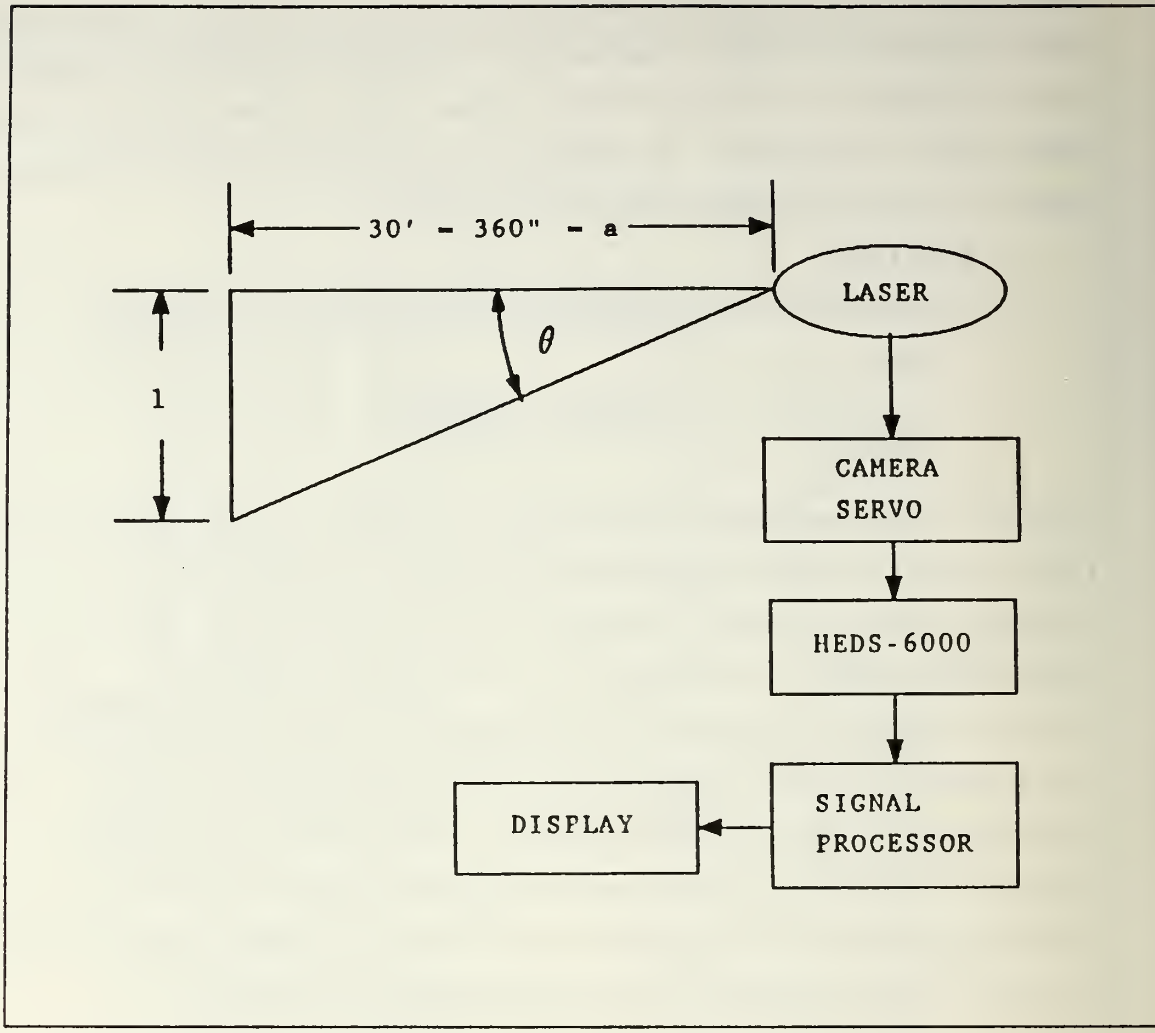


Figure 26. Geometry Used to Determine the Scale Factor

$$\begin{aligned} d(SF) &= \frac{1}{C}\frac{\delta\theta}{\delta l} + \frac{1}{C}\frac{\delta\theta}{\delta a}\,da \\ &= \frac{1}{C}\left(\frac{a}{a^2+l^2}\right)dl + \frac{1}{C}\left(-\frac{l}{a^2+l^2}\right)da \\ d(SF) &= \frac{(a\,dl - l\,da)}{C\left(a^2+l^2\right)} \quad , \end{aligned} \tag{15}$$

which indicates that C, a and l should all be as large as possible to minimize the error in SF due to a measurement error in a or l. The physical size of the laboratory limited the distance, a , to 30 ft. When $a = 30$ ft, l was limited to about 3.5 ft in the horizontal

plane and about 4.0 ft in the vertical plane. By modifying the geometry as shown in Figure 27, the count, which from Equation (13) is directly proportional to θ, could also be maximized. The configuration shown in Figure 27 was used to obtain the scale factor calibration data for the Pan axis. However, since the servo is incapable of rotating 360° about the Tilt axis, the test configuration shown in Figure 26 had to be used the collect the data for that axis.

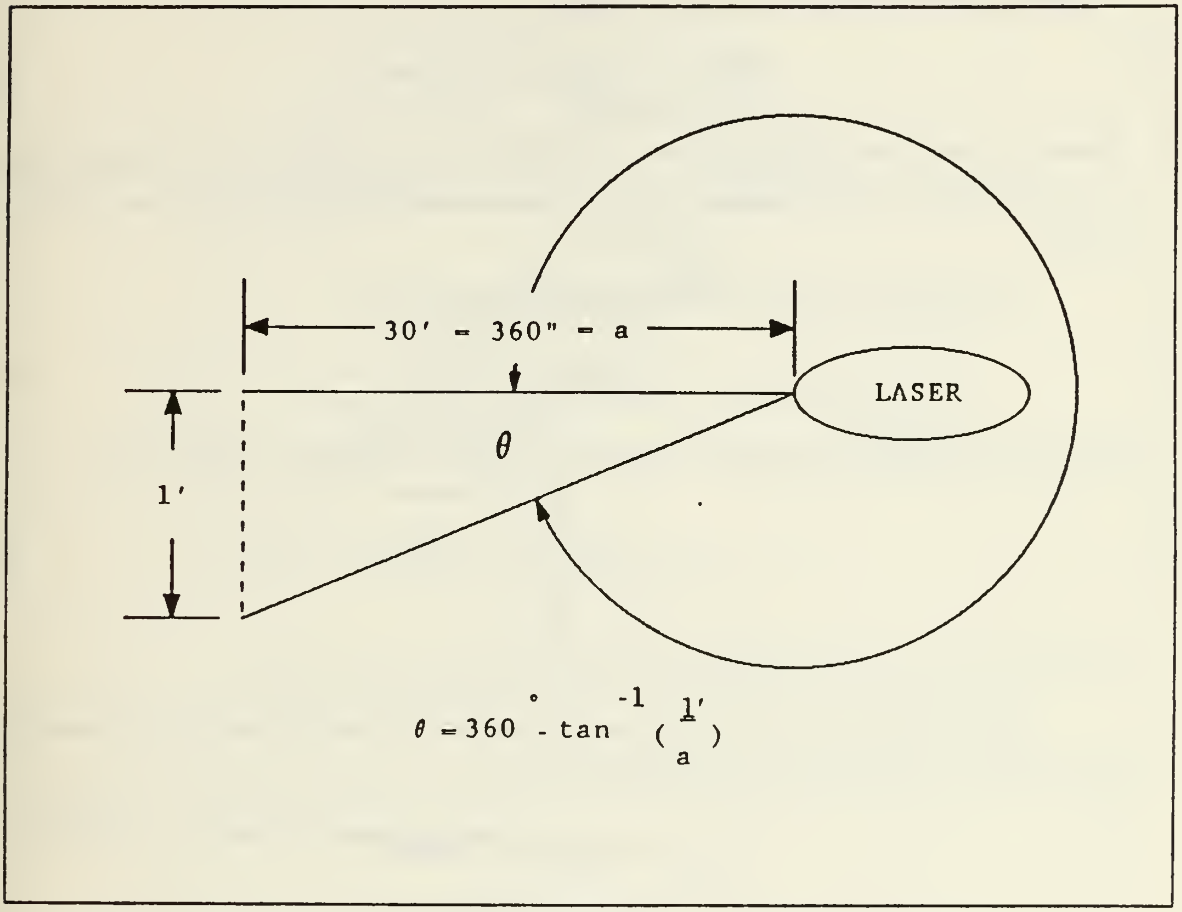


Figure 27. Alternate Geometry Used to Determine the Scale Factor

Adopting the notation, $\overline{X}$, to represent the mean value of a random variable, X; if X is discrete with N measured values,

$$\overline{X} \simeq \frac{1}{N} \sum_{i=1}^{N} X_i \tag{16}$$

where X_i' is the ith measured value of X, and the approximation becomes better as N approaches infinity.

Using the expression in Equation (16) and the measured data for the scale factors, from 31 measurements on the Pan axis,

$$\overline{SF}_{Pan} = (7.0312 \times 10^{-3})°\text{Pulse}^{-1} \ , \tag{17}$$

and after 32 measurements on the Tilt axis,

$$\overline{SF}_{Tilt} = (7.0452 \times 10^{-3})°\text{Pulse}^{-1} \ , \tag{18}$$

where the subscripts indicate the axis. The actual implementation of these scale factors is described later in this chapter and in the documentation for each of the MPU programs.

If the error in the ith measurement is described by

$$e_i = X_i' - \overline{X} \ , \tag{19}$$

then the root mean square (RMS) error in N measurements of X is given by;

$$\sigma_X = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i' - \overline{X})^2} \ . \tag{20}$$

Note that this is also the definition of the standard deviation of X.

The RMS errors in the Pan and Tilt scale factor measurements were determined from Equation (20) and the measured data to be;

$$\sigma_{SF_{Pan}} = (4.62 \times 10^{-6})°\text{Pulse}^{-1} \tag{21}$$

$$\sigma_{SF_{Tilt}} = (6.89 \times 10^{-6})°\text{Pulse}^{-1} \ . \tag{22}$$

As before, the subscripts are used to identify the axis and the source of the error. The fact that the errors are small compared to the mean values suggests that the means should closely approximate the actual values for the scale factors.

2. Hysteresis

Houghton defines backlash in wormgearing as "...the total play between the surfaces of the worm and worm wheel teeth measured normal to the faces." [Ref. 19: pp. 1.4, 1.5] Backlash only poses a problem in the measurement system when the servo's

direction of rotation changes. Figure 28 is a typical hysteresis curve. As long as the direction of rotation of the worm is increasing the $\theta_{WORM}/\theta_{WORMGEAR}$ relationship is linear. However, when the direction of rotation reverses there is a region, depicted by the left pointing arrows, where the position of the worm changes without a corresponding change in the position of the wormgear. Note that once all of the backlash has been taken up the $\theta_{WORM}/\theta_{WORMGEAR}$ relationship is again linear until the direction of rotation changes.

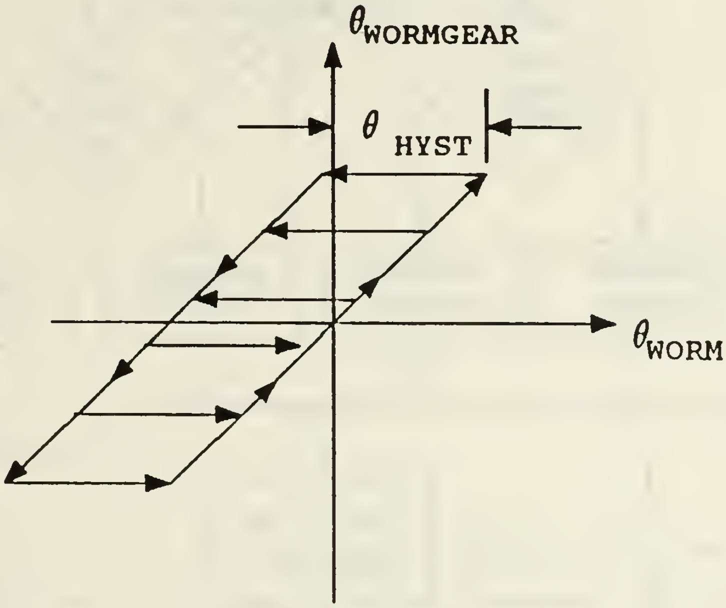


Figure 28. Typical Hysteresis Curve

The purpose of the hysteresis buffer in the MPU is to permit the signal processor to account for the backlash error introduced into the measurement by the worm-wormgear connection. The theory of operation for the buffer is relatively straight forward and is best described by the flow diagram in Figure 29. The buffer is a data byte in the MPU RAM. As long as the buffer is full, i.e., the contents are equal to the predetermined buffer length, a clockwise (CW) signal from the shaft encoder (increasing elevation and increasing azimuth are defined as CW rotation for the purposes of this system) causes the position counter to be incremented. Similarly, counter-clockwise

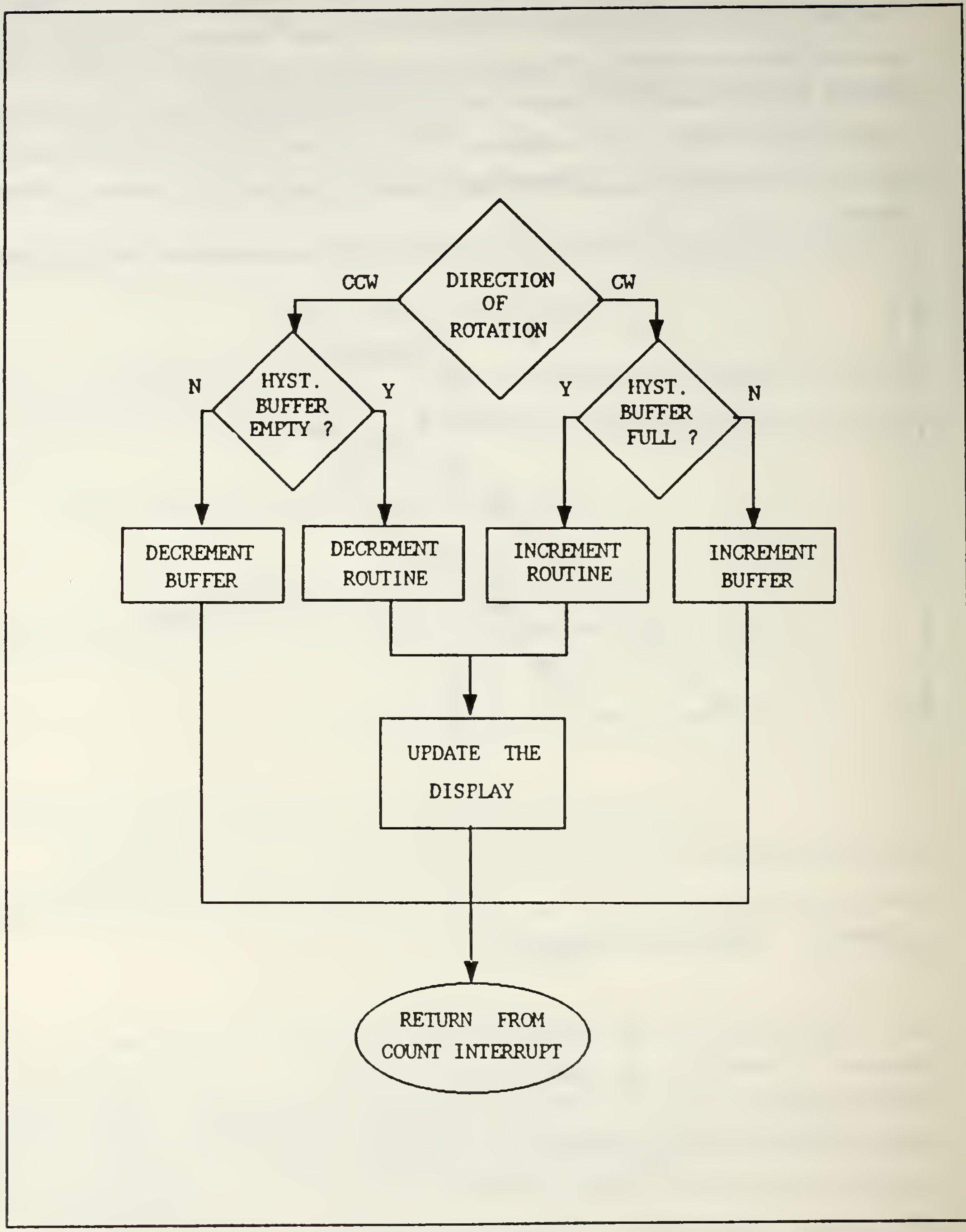


Figure 29. Operation of the Hysteresis Buffer

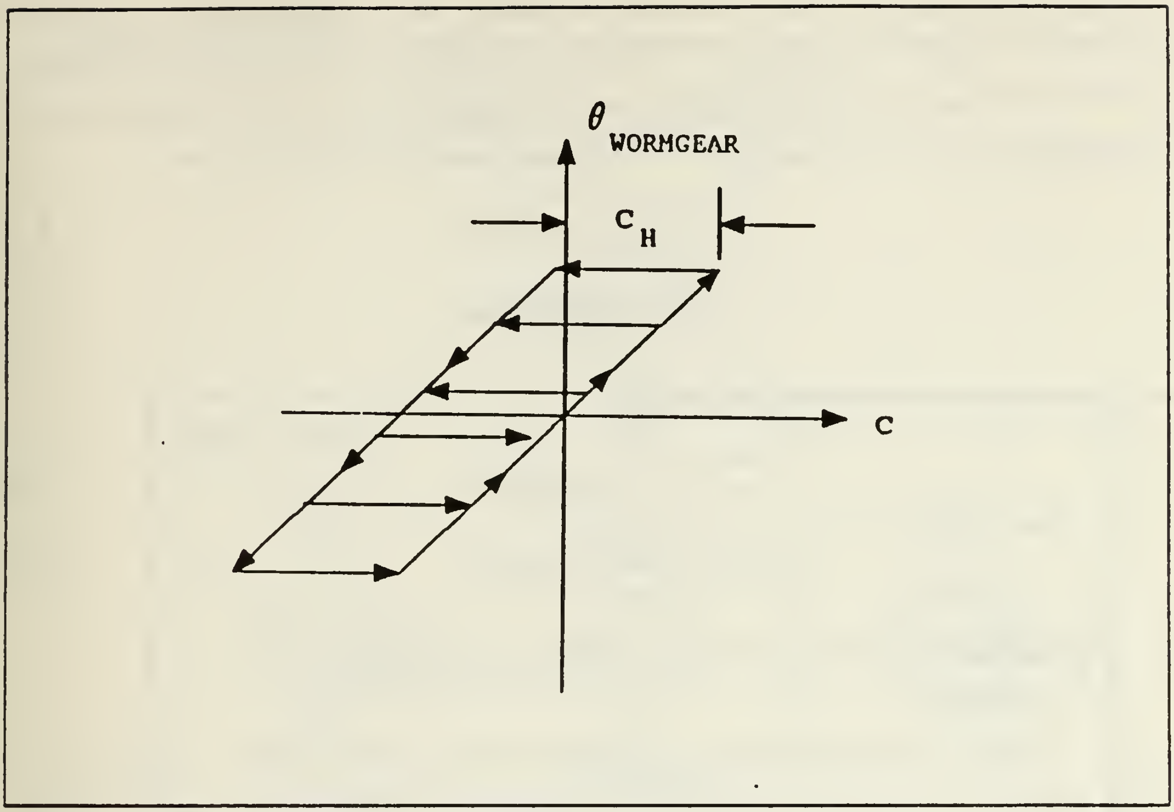


Figure 30. Hysteresis Curve

(CCW) signals cause the position counter to be decremented if the hysteresis buffer is empty, i.e., the contents are equal to zero. These two situations correspond to the two linear sections in Figure 28. From Equation (13), the horizontal separation of these two lines is related to the length of the hysteresis buffer, C_H by the expression

$$C_H = \frac{\Delta\theta_H}{SF} \quad . \tag{23}$$

Similarly, using the $\overline{SF}$ to map θ_{WORM} into C, and the fact that the displacement of the wormgear equals the displacement of the axis of interest, the curve shown in Figure 30 can be obtained from Figure 28. From Figure 30 it is apparent that two different pulse counts can be obtained for any given position, θ, depending on whether that position is approached from a CW or a CCW direction. The difference in the two counts is a measure of the hysteresis present in the gear train and is also the required length for the hysteresis buffer. By using this difference as the length of the hysteresis buffer, counts received by the MPU which occur while the gears are operating on one of the horizontal

sections of the curve in Figure 30 are not considered "valid" and therefore do not cause the MPU to modify the position. Using Equation (23) and data collected in the laboratory the average hysteresis present in each of the gear trains was determined (from 45 measurements on the Pan axis and 30 measurements on the Tilt axis) to be

$$\overline{C}_{H(Pan)} = 7.39 \text{ Pulses} \qquad (24)$$

$$\overline{C}_{H(Tilt)} = 6.06 \text{ Pulses} \qquad (25)$$

and the RMS errors were calculated to be,

$$\sigma_{C_{H(Pan)}} = 1.0 \text{ Pulses} \qquad (26)$$

$$\sigma_{C_{H(Tilt)}} = 0.91 \text{ Pulses} \ . \qquad (27)$$

C. IMPLEMENTATION OF THE CALIBRATION DATA

1. Background

Figure 31 outlines the basic operation of each of the MPU's. Although each of the routines is described in detail by the comments included in the programs, the operation of the Count Routine is the heart of the program and should be explained prior to discussing the actual implementation of the experimental results.

When the system operator causes the camera servo to rotate, each optical shaft encoder translates the displacement of one of the axes into two series of digital pulses. The two pulse trains, referred to as Channels A and B, are TTL logic level signals. When the logic level of Channel A transitions from low to high (rising edge transition) or from high to low (falling edge transition), the edge detector (See Figure 15 on page 33) pulls pin 3 of the associated MPU low for approximately 2 μsec. When this occurs an external interrupt (EXT INT or $\overline{\text{INT}}$) request is generated and the MPU begins execution of the Count Routine.

As mentioned in Chapter III, since both rising and falling edge transitions are detected by the edge detector, the signal processor must be capable of detecting multiple oscillations of the shaft about a single logic level transition point. Accordingly, the first tasks performed by the Count Routine are to determine the direction of rotation and to simultaneously determine whether the interrupt is the result of a stationary shaft oscillation. To do this the Count Routine checks the state of pin 17 (Channel A) and pin 19 (Channel B). Operation of this portion of the routine is summarized in Table 5.

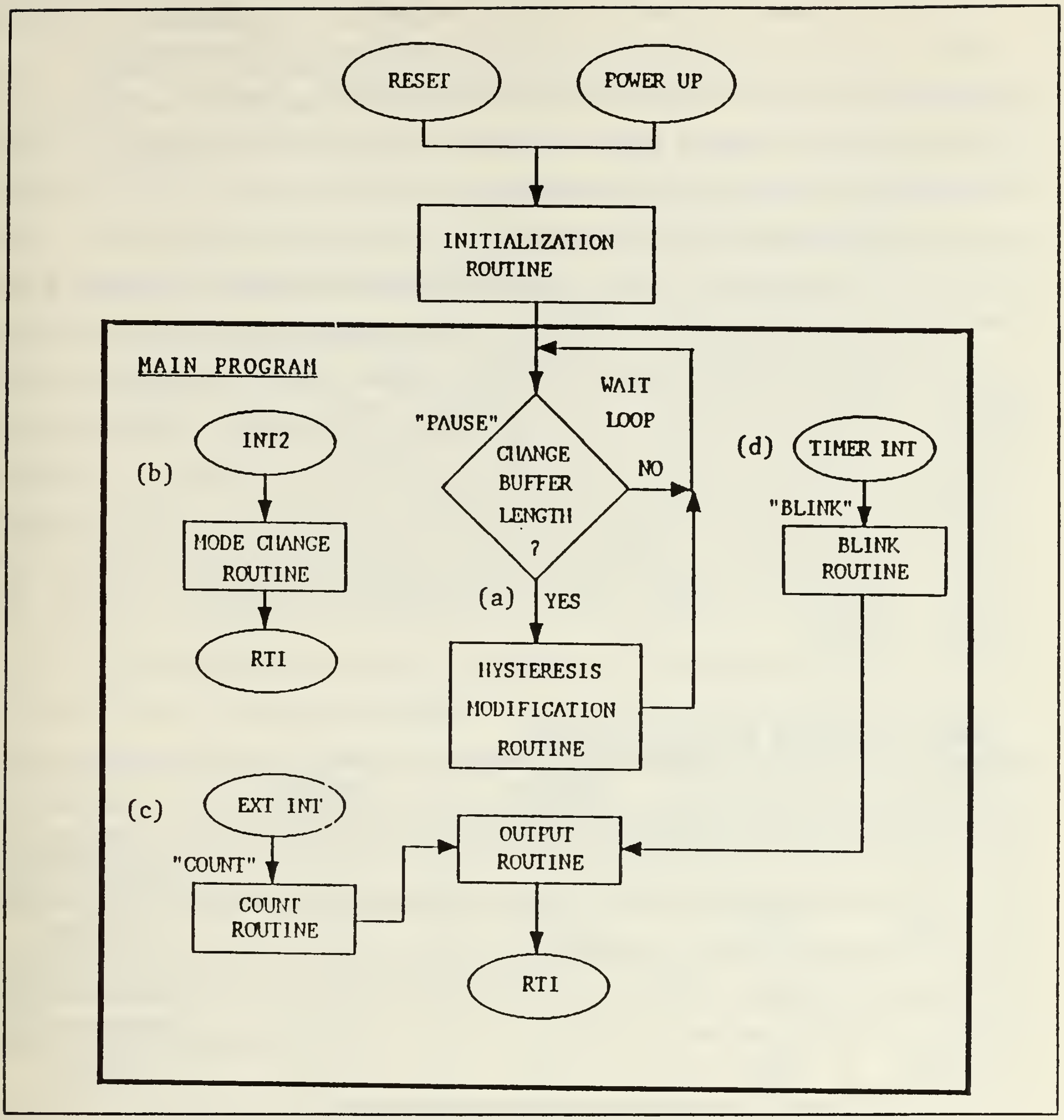


Figure 31. Program Flow Diagram: Program executes in the Wait Loop until; (a) the operator requests to modify the hysteresis buffer, (b) the operator requests to change the display mode, (c) an external interrupt is generated by the Channel A edge detector or, (d) a timer interrupt causes the display mode to "blink". All interrupt routines are terminated with a return from interrupt (RTI) command.

Note that CW rotation is indicated when Channel B leads Channel A in phase and CCW rotation is indicated if Channel A is leading Channel B. The possibility of erroneously counting multiple oscillations about a single point is eliminated by "counting" only the leading edge transitions when the shaft is rotating CW and only the trailing edge transitions when the rotation is CCW. All other transitions cause the program to execute a "return from interrupt" (RTI) instruction.

2. Implementing the Hysteresis Buffer

The transitions that are to be counted cause the program to compare the contents of the hysteresis buffer, HYSTCT, and the direction of rotation to the experimentally determined buffer length, HYST$\simeq\overline{C}_H$. If the rotation is CW and the buffer is full (i.e., HYSTCT=HYST), or if the rotation is CCW and the buffer is empty (i.e., HYSTCT=0), then the "slack" due to the gear backlash should have been taken up , the transitions are considered "valid" and the MPU modifies the position appropriately. "Invalid" counts cause the contents of the hysteresis buffer to be incremented or decremented depending on whether the present direction of rotation is CW or CCW (Figure 29 refers).

Table 5. COUNT ROUTINE LOGIC

Channel A	Channel B	Direction of Rotation	Count the Pulse?	Action
Low	Low	CW	No	Increment the hysteresis buffer.
Low	High	CCW	Yes	Decrement the position.
High	Low	CCW	No	Decrement the hysteresis buffer.
High	High	CW	Yes	Increment the position.

From the calibration data for the Pan axis, $\overline{C}_{H(Pan)}\simeq 7.4$ and $\sigma_{C_{H(Pan)}}\simeq 1.0$. Because the length of the hysteresis buffer must be an integer value, $\overline{C}_{H(Pan)}$, needed to be rounded off. Rounding to the nearest whole number initially seemed the most logical approach. Upon further consideration, however, it was decided to round 7.4 up to 8. Considering the relatively small data base (45 measurements) upon which the average was based, the fact that the standard deviation was 1.0 and that the gear backlash will only increase

with time, this seemed like the most reasonable approach. The buffer length for the Tilt axis was set equal to 6 ($\overline{C}_{H(Tilt)} = 6.06$) .

3. Implementing the Scale Factor

There are three counters in each MPU that keep track of the position information for the axis of interest. The first, BINCT, is simply a binary counter that is incremented by one for each valid CW count and decremented by one for each valid CCW count. The other two counters consist of two sets of pointers, two sets of data registers and a shared data table. Each byte in a pointer points to an address in the table that contains two BCD digits which make up a portion of the position information.

In order to increment (decrement) the pulse count, BCDCT, by one, the count pointer, CTPTR, is incremented (decremented) by one causing it to point to a new table address. The contents of the table at the new addresses are then moved into BCDCT. Modification of the position counter, DEGRES, is performed in much the same manner. DEGRES contains a BCD number that, when multiplied by 0.001, represents the angular position (in degrees) of the shaft of interest. Thus, each time the camera is displaced in a CW direction through one degree, the contents of DEGRES should be incremented by 1000. To do this, the position pointer, PTR, must be incremented (decremented) by seven or eight each time CTPTR is incremented (decremented) by one. Incrementing PTR by seven corresponds to an angular displacement of 0.007° and since $\overline{SF}_{Pan}$ and $\overline{SF}_{Tilt}$ are each slightly larger than 0.007°, periodically PTR must be incremented by eight to reduce the cumulative round off error. Specifically, if PTR is incremented by seven each time a valid CW pulse is detected (except when BINCT is an even multiple of 32) and is incremented by eight when BINCT is a modulo 32 number, the effective scale factor is given by:

$$\begin{aligned} SF_{eff_1} &= \frac{1}{32}(31(0.007) + 0.008) \\ &= 0.00703125°\text{Pulse}^{-1} \ , \end{aligned} \tag{28}$$

which is slightly larger than the desired 0.0070312°Pulse^{-1}, for the Pan axis and slightly smaller than the desired 0.0070452°Pulse^{-1} for the Tilt axis. To further reduce the cumulative round off on the Pan axis, every 16,384 ($2^{14} = 32 \times 512$) counts PTR is incremented by seven instead of eight. This results in an effective scale factor of,

$$
\begin{aligned}
SF_{eff_2} &= \frac{1}{512}\left\{511\left[\frac{1}{32}(31(7)+8)\times 10^{-3}\right]+0.007\right\} \\
&= \left(7.03119\times 10^{-3}\right)^\circ \text{Pulse}^{-1} \ ,
\end{aligned} \tag{29}
$$

which is within two parts in one million.

The maximum error introduced into the measurement should occur when the camera is rotated through the largest possible angle. To predict this error on the Pan axis, when the camera has been displaced by 360°,

$$
\begin{aligned}
BCDCT &= \frac{360^\circ}{\overline{SF}_{Pan}} \\
&= 51{,}200 \text{ Pulses}
\end{aligned} \tag{30}
$$

so the position error using SF_{eff_1} and SF_{eff_2} should be;

$$
\begin{aligned}
e_{Pan} &= 360^\circ - [3(SF_{eff_2}) + (51{,}200 - 3(16{,}384))(S_{eff_1})] \\
&= 0.00295^\circ \ .
\end{aligned} \tag{31}
$$

Thus, the error due to the scale factor on the Pan axis should be well within the desired resolution of $\pm 0.006^\circ$.

Using SF_{eff_1} alone as the scale factor for the Tilt axis, the maximum theoretical error over $\pm 12^\circ$ due to the scale factor round off is determined in the same manner.

$$
\begin{aligned}
BCDCT &= \frac{12^\circ}{\overline{SF}_{Tilt}} \\
&= 17{,}033 \text{ Pulses}
\end{aligned} \tag{32}
$$

So that,

$$
\begin{aligned}
e_{Tilt} &= 12^\circ - 17{,}033(SF_{eff_1}) \\
&= 0.0234^\circ \ ,
\end{aligned} \tag{33}
$$

which again is significantly less than the required resolution of $\pm 0.23^\circ$ for the Tilt axis.

The final step in the Count Routine is a branch to the Display Routine. Depending on whether the MPU is in the Count or Position Mode, the Display Routine copies the contents of BCDCT or DEGRES to the output ports and then executes an RTI instruction.

D. FINAL TESTING

1. General

Final laboratory testing and evaluation of the measurement system was performed after the calibration results had been implemented in each of the MPU Count Routines. The purpose of the testing was to verify that the calibration results had been properly coded into the MPU's and to determine the resolution capabilities of the measurement system experimentally.

This verification process included determining the combined error due to the hysteresis and scale factor errors. The use of some simple multiple random variable theory was therefore required. From [Ref. 20: pp. 121,122] the variance of a weighted sum of M random variables is the weighted sum of their covariances, $C_{X_iX_j}$, and is given by,

$$\sigma^2 = \sum_{i=1}^{M} \sum_{j=1}^{M} \alpha_i \alpha_j C_{X_iX_j} \ , \tag{34}$$

where α_i is the weight associated with X_i. Additionally, the covariance can be expressed as

$$C_{XY} = \rho \sigma_X \sigma_Y \ , \tag{35}$$

where ρ is the normalized second-order moment and is known as the correlation coefficient of X and Y. The correlation coefficient is bounded by

$$-1 \leq \rho \leq 1 \ . \tag{36}$$

In the case where there are two equally weighted random variables, $M = 2$ and $\alpha_i = \alpha_j = 1.0$. Substituting into Equation (34) and expanding

$$\sigma^2 = C_{XX} + C_{XY} + C_{YX} + C_{YY} \ . \tag{37}$$

Using Equation (35),

$$\sigma^2 = \sigma_X^2 + 2\rho\sigma_X\sigma_Y + \sigma_Y^2 \ . \tag{38}$$

Combining (36) and (38) yields

$$\sigma_X^2 - 2\sigma_X\sigma_Y + \sigma_Y^2 \leq \sigma^2 \leq \sigma_X^2 + 2\sigma_X\sigma_Y + \sigma_Y^2 \ . \tag{39}$$

The bounds of the combined scale factor and hysteresis errors can therefore be determined from

$$\sqrt{\sigma_{e_{SF}}^2 - 2\sigma_{e_{SF}}\sigma_{e_H} + \sigma_{e_H}^2} \leq \sigma_e \leq \sqrt{\sigma_{e_{SF}}^2 + 2\sigma_{e_{SF}}\sigma_{e_H} + \sigma_{e_H}^2} \quad . \tag{40}$$

where:

- σ_e = standard deviation of the combined error,
- $\sigma_{e_{SF}}$ = standard deviation of the scale factor error, and
- σ_{e_H} = standard deviation of the hysteresis error.

Note that the bounds are determined by the two cases where the hysteresis error, e_H, and the scale factor error, e_{SF}, are "completely correlated". The upper bound corresponds to the case where an increase in e_{SF} implies an increase in e_H, and the lower bound corresponds to the case where an increase in e_{SF} directly implies a decrease in e_H.

A third case is also of particular interest. If e_H and e_{SF} are completely uncorrelated, i.e., $\rho = 0$, then from Equation (38),

$$\sigma_e = \sqrt{\sigma_{e_{SF}}^2 + \sigma_{e_H}^2} \quad . \tag{41}$$

which can also be written as

$$e = \pm\sqrt{e_{SF}^2 + e_H^2} \quad , \tag{42}$$

where $e = \pm\,\sigma_e$ is the 1.0 σ error due to the scale factor and hysteresis errors, e_{SF} and e_H respectively. Based on the physical nature of the two errors it is reasonable to assume that e_{SF} and e_H are statistically uncorrelated; however, no experimental data was collected to support this hypothesis. Due to this lack of a priori information, the maximum RMS error, $e_{max} = \pm\,\sigma_{e_{max}}$, given by

$$e_{max} = \pm\sqrt{e_{SF}^2 + 2e_{SF}e_H + e_H^2} \quad , \tag{43}$$

will be used to describe the resolution capabilities of the measurement system.

2. Pan Axis

a. Hysteresis

To test the operation of the Pan axis hysteresis buffer, the Initialization Routine was programmed to set the buffer length to 8. Then, as described in the first section of this chapter, the servo was used to position the beam of a small laser on a fixed target. By approaching the target alternately from a CW and a CCW direction and

comparing the difference in the output counts from the shaft encoders, the hysteresis error was determined. The average error after 31 measurements was

$$\bar{e}_{H(Pan)} = -0.1880 \text{ Pulses} \ , \tag{44}$$

and the RMS error was

$$\sigma_{e_{H(Pan)}} = 1.7699 \text{ Pulses} \ . \tag{45}$$

Since the mean error is "near zero" compared to the standard deviation, the 1.0 σ error e_H, due to the hysteresis can be determined from

$$e_H = \pm (\sigma_{e_H})\overline{SF} \tag{46}$$

so that

$$e_{H(Pan)} = \pm\, 0.0124° \ . \tag{47}$$

b. Scale Factor

Verification of the scale factor was performed in the same manner as the scale factor calibration, except that the MPU was calibrated in the Count Mode and tested in the Position Mode. Since these tests sought to find the maximum error due to the scale factor, and the error is directly proportional to the angle that is being measured, these tests were conducted by displacing the camera servo through the maximum angles permitted by the camera and the laboratory. Specifically, on the Pan axis the servo was rotated through approximately 360°. The mean error due to the scale factor on the Pan axis was determined from 15 samples to be

$$\bar{e}_{SF(Pan)} = -0.0018° \tag{48}$$

and the RMS error was

$$\sigma_{e_{SF(Pan)}} = 0.00890° \ . \tag{49}$$

As with the hysteresis error, if we neglect the small bias due to the $\bar{e}_{SF(Pan)}$, we can describe the 1.0 σ RMS error due to the scale factor as

$$\begin{aligned} e_{SF(Pan)} &= \pm\, \sigma_{SF(Pan)} \\ &= \pm\, 0.00890° \end{aligned} \tag{50}$$

c. Combined Error

From Equation (42) the combined error on the Pan axis if e_H and e_{SF} are uncorrelated can be estimated as

$$\begin{aligned} e_{Pan} &= \pm\sqrt{(0.0124)^2 + (0.0089)^2} \\ &= \pm\, 0.01526^\circ \ . \end{aligned} \tag{51}$$

And from Equation (43) the maximum combined error on the Pan axis is

$$e_{Pan_{max}} = \pm\sqrt{(0.0124)^2 + 2(0.0124)(0.0089) + (0.0089)^2} \tag{52}$$

$$\boxed{e_{Pan_{max}} = \pm\, 0.0213^\circ \ .} \tag{53}$$

The combined error is approximately three times larger than the design specification limit and is due primarily to the hysteresis error.

3. Tilt Axis

a. Hysteresis

The procedure used to verify the operation of the calibrated Tilt MPU was identical to that described in the previous section. Using a hysteresis buffer length of 6 resulted in

$$\bar{e}_{H(Tilt)} = -0.0965 \text{ Pulses} \tag{54}$$

and,

$$\sigma_{e_{H(Tilt)}} = 1.3156 \text{ Pulses} \tag{55}$$

after 13 samples. As before we can define the 1.0 σ error from $e = \sigma\overline{SF}$ to be

$$e_{H_{Tilt}} = \pm\, 0.00529^\circ \ . \tag{56}$$

b. Scale Factor

Testing the scale factor on the Tilt axis was limited by the physical construction of the servo and the size of the laboratory. The angle over which testing could be performed was limited to $\pm\, 6^\circ$ from the horizontal plane. Consequently, the RMS error for the scale factor on the Tilt axis was determined in exactly the same manner as

the RMS error for the Pan axis scale factor, but since the error due to rounding of the scale factor is directly proportional to the angle being measured the results were multiplied by 2.0 to account for the limited range of the test. The modified results should therefore be representative of the maximum error one should expect if the measurement system is used to measure elevation angles over a range of $\pm 12°$.

The error due to the scale factor is described from 16 samples by

$$\bar{e}_{SF(Tilt)} = 0.0070° \tag{57}$$

and,

$$\sigma_{e_{SF(Tilt)}} = 0.0665° \ . \tag{58}$$

Including the factor of two in the calculation we have

$$\begin{aligned} e_{SF(Tilt)} &= \pm\, 2(0.0665°) \\ &= \pm\, 0.1330° \ . \end{aligned} \tag{59}$$

c. Combined Error

The combined RMS error is determined in the same manner as before. If e_H and e_{SF} are uncorrelated,

$$\begin{aligned} e_{Tilt} &= \pm\sqrt{(0.1330)^2 + (0.00529)^2} \\ &= 0.1331° \ , \end{aligned} \tag{60}$$

and the maximum combined RMS error is

$$e_{Tilt_{max}} = \pm\sqrt{(0.1330)^2 + 2(0.1330)(0.00529) + (0.00529)^2} \tag{61}$$

$$\boxed{e_{Tilt_{max}} = \pm\, 0.1383° \ .} \tag{62}$$

The Tilt axis measurement system appears to perform well within the required resolution specifications.

E. FINAL IMPLEMENTATION

Once the program debugging, calibration and testing were completed, final implementation of the system remained. Taking the design from the prototype/development model to a fully functional system was a straightforward but time-consuming evolution.

The plans for the printed circuit boards (PCB's) were made directly from the schematics shown in Appendix A; the boards were then etched and assembled from the plans which are shown in Appendix B. All of this work was performed by sailors attached to the Academic Division of the NPS.

As previously discussed, the M68705EVM Evaluation Module provided a powerful and flexible means of debugging and evaluating the performance of the microprocessor based signal conditioner. Additionally, once program testing was completed the EVM's EPROM microprocessor programmer provided the means to program the EPROM MCU's. A detailed, but simple to follow, programming procedure for programming the MC68705U3 is given in [Ref. 18: pp. (3-26)-(3-27)].

V. CONCLUSIONS AND RECOMMENDATIONS

A. SYSTEM PERFORMANCE

The prototype system was calibrated and successfully tested in a laboratory environment. Experimental results indicate that the system is capable of measuring the video camera's elevation over a range of $\pm 12°$ with a resolution of $\pm 0.138°$ and its azimuth over 360° with a resolution of $\pm 0.021°$. The system was designed to be low cost, reliable, and easy to operate. Only time will tell whether these objectives were truly achieved.

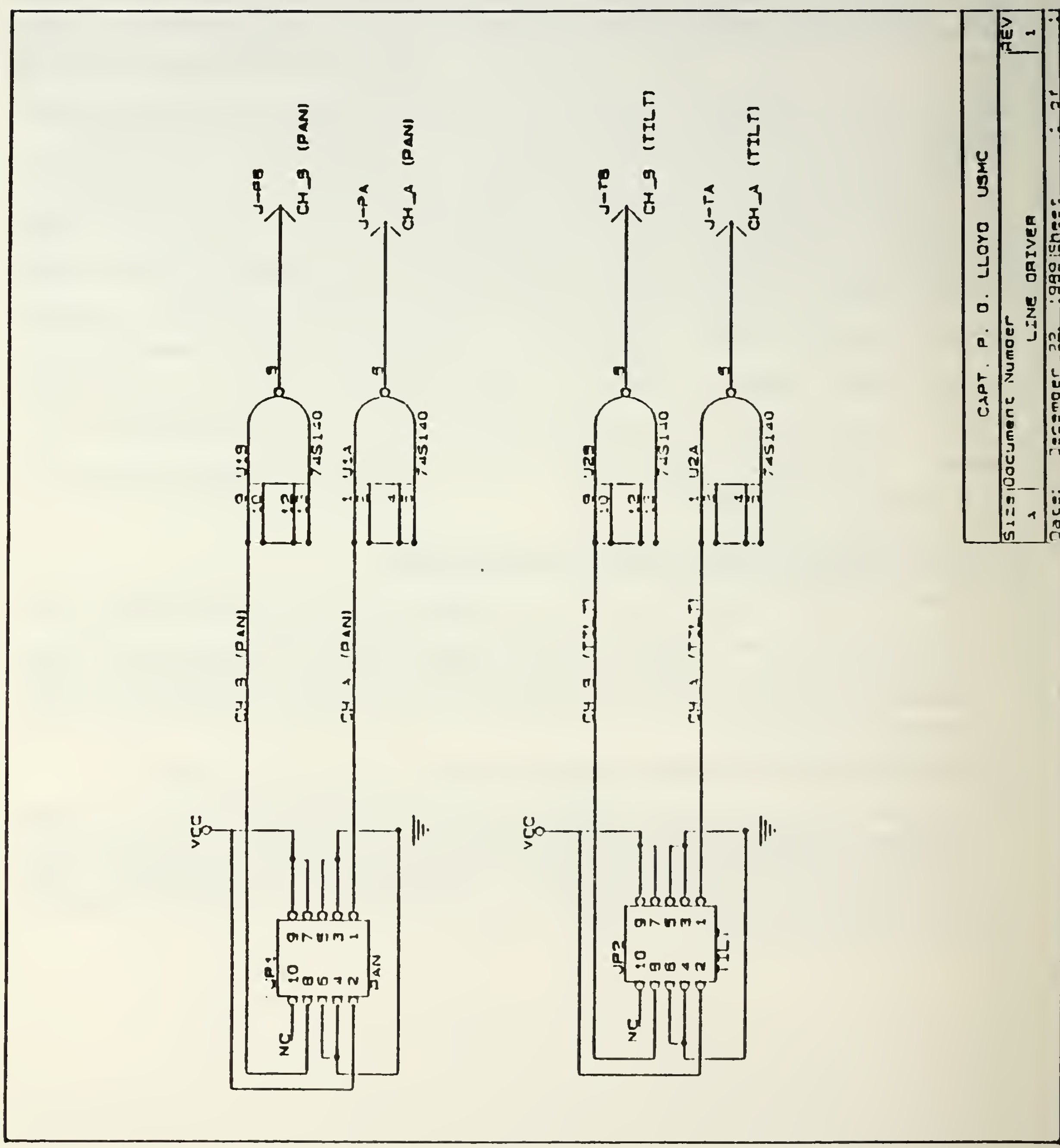
The portion of the system that will be located outdoors has been weatherproofed and is ready to be placed in service. Printed circuit board plans for the remainder of the system have been developed, but final implementation of the system is still ongoing. Once the system is fully operation additional testing should be performed in order to verify the completed system's performance. Although the laboratory results indicate that the system is capable of meeting all of the design criteria except for the required resolution on the Pan axis, the system must be further tested in a non-laboratory environment. "...The proof of a good design rests in the ability of the system to function in the outside world." [Ref 21]

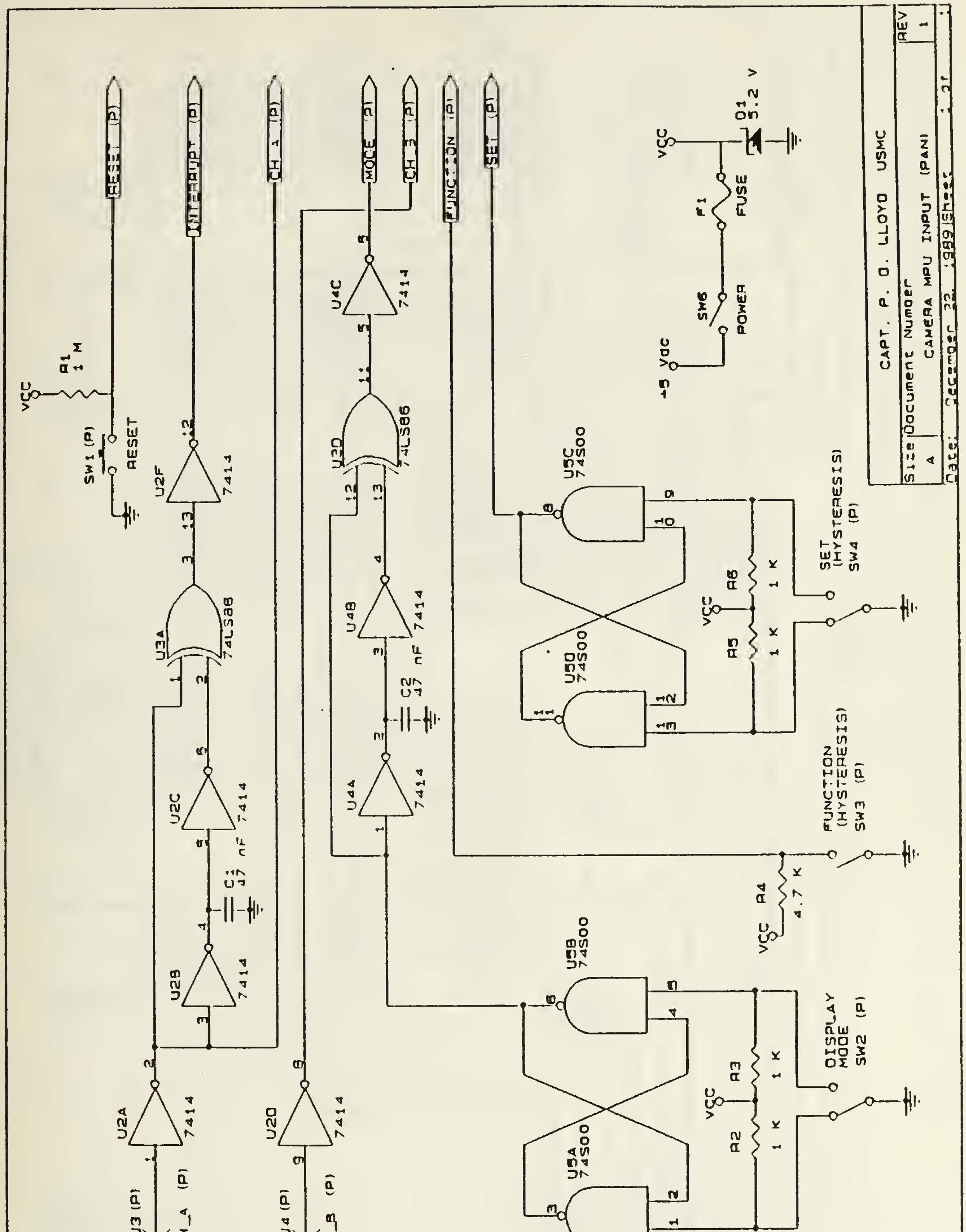
B. RECOMMENDATIONS FOR FURTHER WORK

There are several areas for follow-on work with this project. Some possibilities are:

- Incorporate the measurement system's output into the video image being created by the video camera. This would permit a permanent record of the position information to be stored with the video image and would facilitate identification of the image at a later date.
- Design and build an automatic feedback control system for the camera.
- Implementation of a second video camera at the NPS, together with the NPS modified IRSTD, would permit triangulation of a target and would consequently provide range information which is not currently available. This information could provide valuable additional information to those who are developing the signal processing algorithms.

APPENDIX A. SCHEMATIC DIAGRAMS

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INTERRUPT (P)
MODE (P)
SET (P)
VCC
R1 1 M
SW1 (P) RESET
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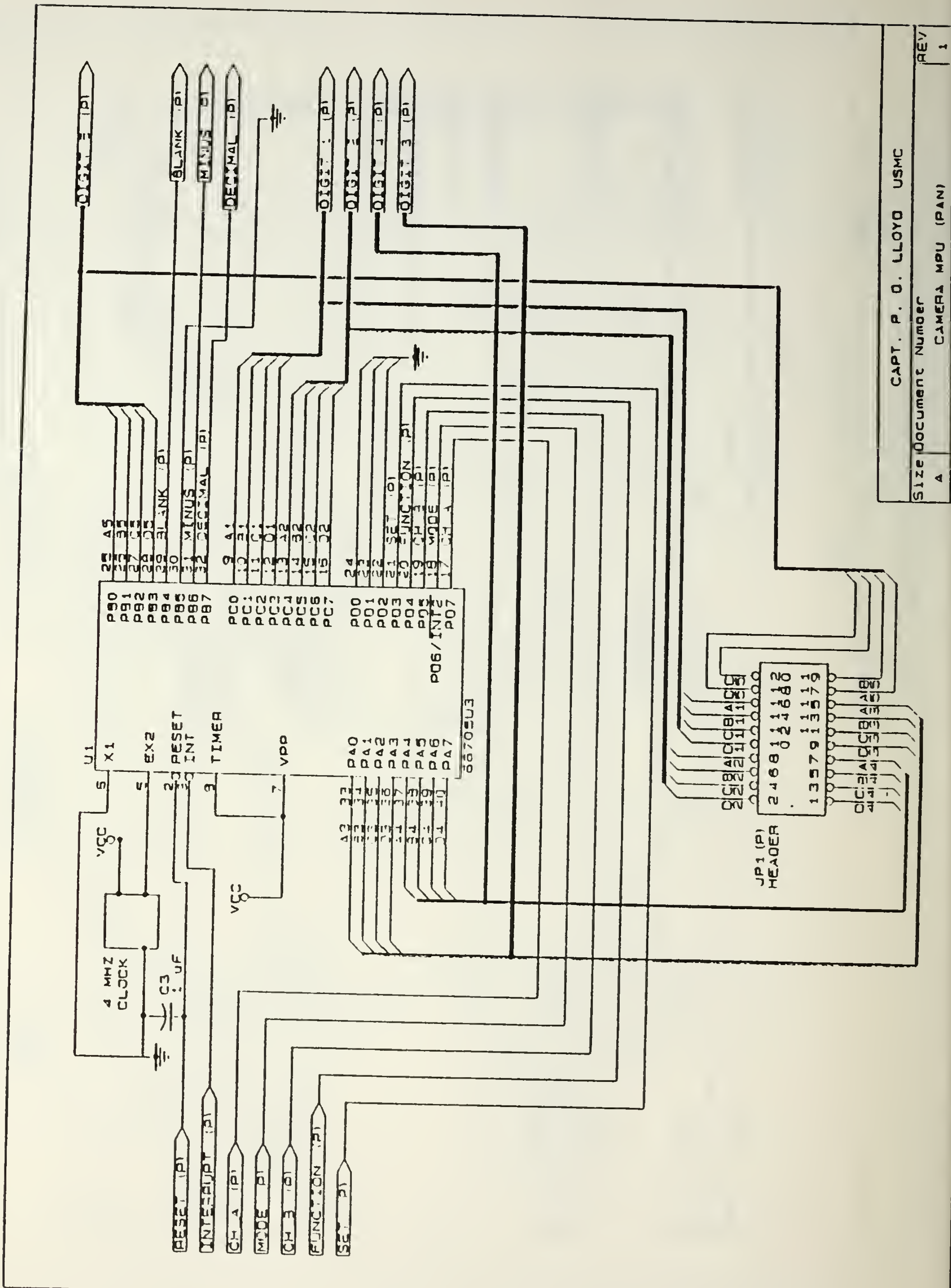
U2B 7414
U2C 7414
U2D 7414
U2F 7414
U3A 74LS86
U3D 74LS86
U4A 7414
U4B 7414
U4C 7414
U5A 74S00
U5B 74S00
U5C 74S00
U5D 74S00
J3 (P) CH_A (P)
J4 (P) CH_B (P)
R2 1 K
R3 1 K
R4 4.7 K
R5 1 K
R6 1 K
DISPLAY MODE SW2 (P)
FUNCTION (HYSTERESIS) SW3 (P)
SET (HYSTERESIS) SW4 (P)
+5 Vdc
SW6 POWER
F1 FUSE
D1 5.2 V


CAPT. P. D. LLOYD USMC
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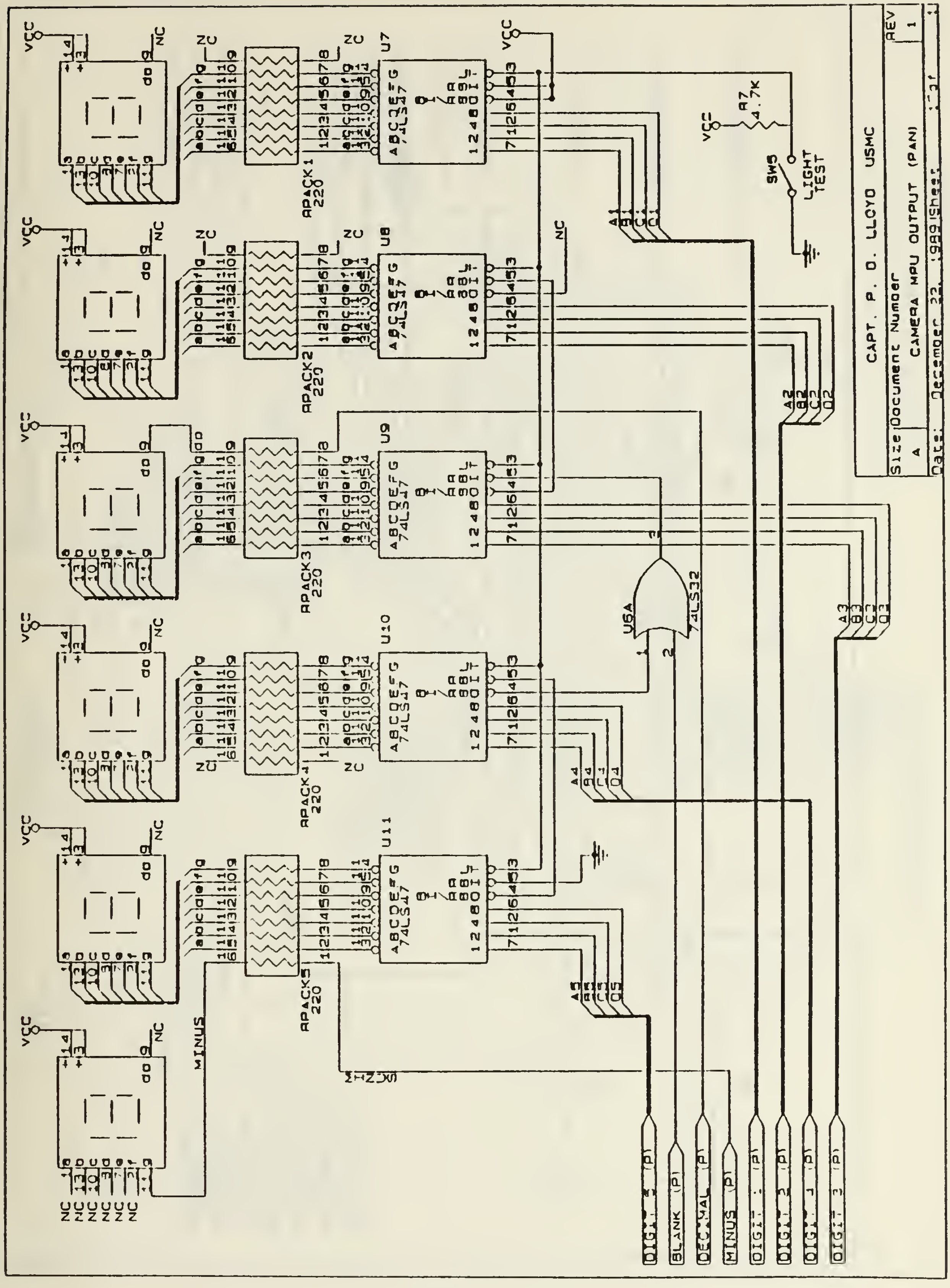
A
Document Number
CAMERA MPU (PAN)
REV
1
Date: December 22, 1989
JP1 (P) HEADER
4 MHZ CLOCK
C3
VCC
U1
X1
EX2
RESET
INT
TIMER
VPP
PB0
PB1
PB2
PB3
PB4
PB5
PB6
PB7
PC0
PC1
PC2
PC3
PC4
PC5
PC6
PC7
PD0
PD1
PD2
PD3
PD4
PD5
PD6/INT2
PD7
PA0
PA1
PA2
PA3
PA4
PA5
PA6
PA7
BLANK (P)
MINUS (P)
DECIMAL (P)
RESET (P)
INTERRUPT (P)
CH A (P)
MODE (P)
CH B (P)
FUNCTION (P)


CAPT. P. D. LLOYD USMC
Size
Document Number
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REV
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BLANK (P)
MINUS (P)
MINUS
LIGHT TEST
SW5
R7
4.7K
74LS32
74LS47
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U10
U11
VCC
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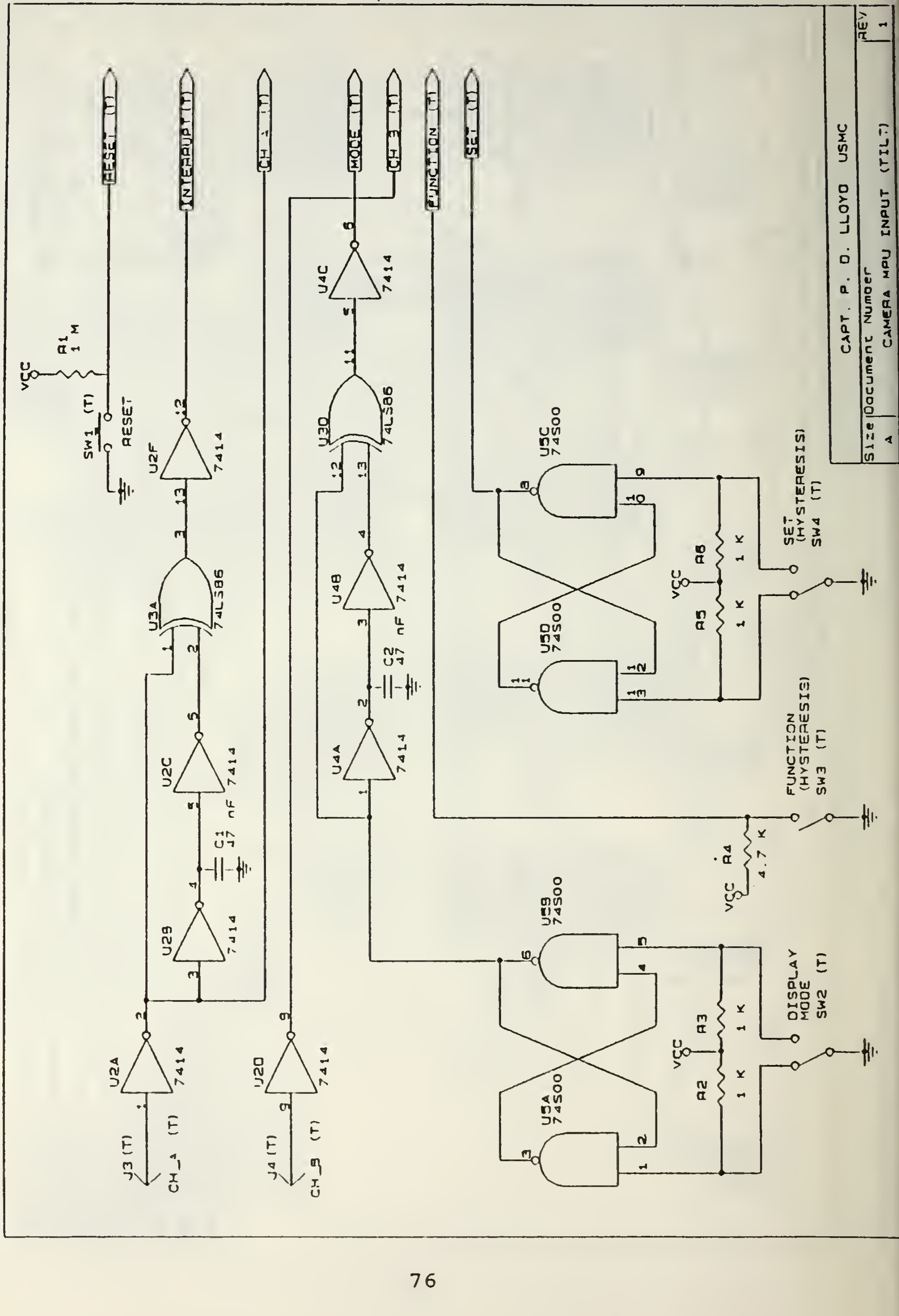
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Document Number
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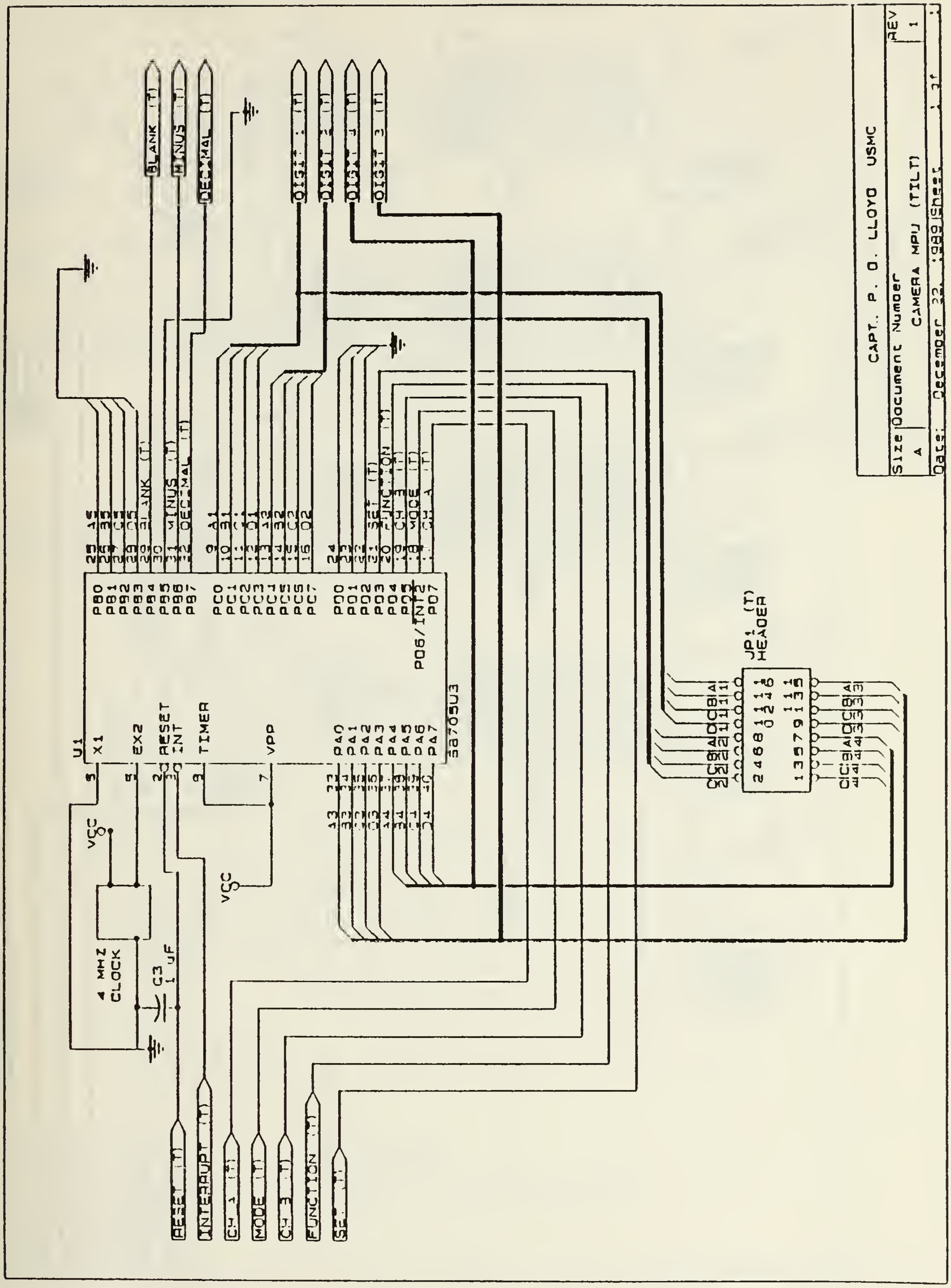
INTERRUPT (T)
CH 1 (T)
MODE (T)
CH 3 (T)
FUNCTION (T)
SET (T)
VCC
R1 1 M
SW1 (T) RESET
U2F 7414
U3A 74LS86
U2C 7414
C1 47 nF
U2B 7414
U2A 7414
J3 (T) CH_A (T)
U2D 7414
J4 (T) CH_B (T)
U4C 7414
U3D 74LS86
U4B 7414
C2 47 nF
U4A 7414
U5C 74S00
U5D 74S00
U5B 74S00
U5A 74S00
R8 1 K
R5 1 K
R4 4.7 K
R3 1 K
R2 1 K
SET (HYSTERESIS) SW4 (T)
FUNCTION (HYSTERESIS) SW3 (T)
DISPLAY MODE SW2 (T)



CAPT. P. D. LLOYD USMC
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JP1 (T)
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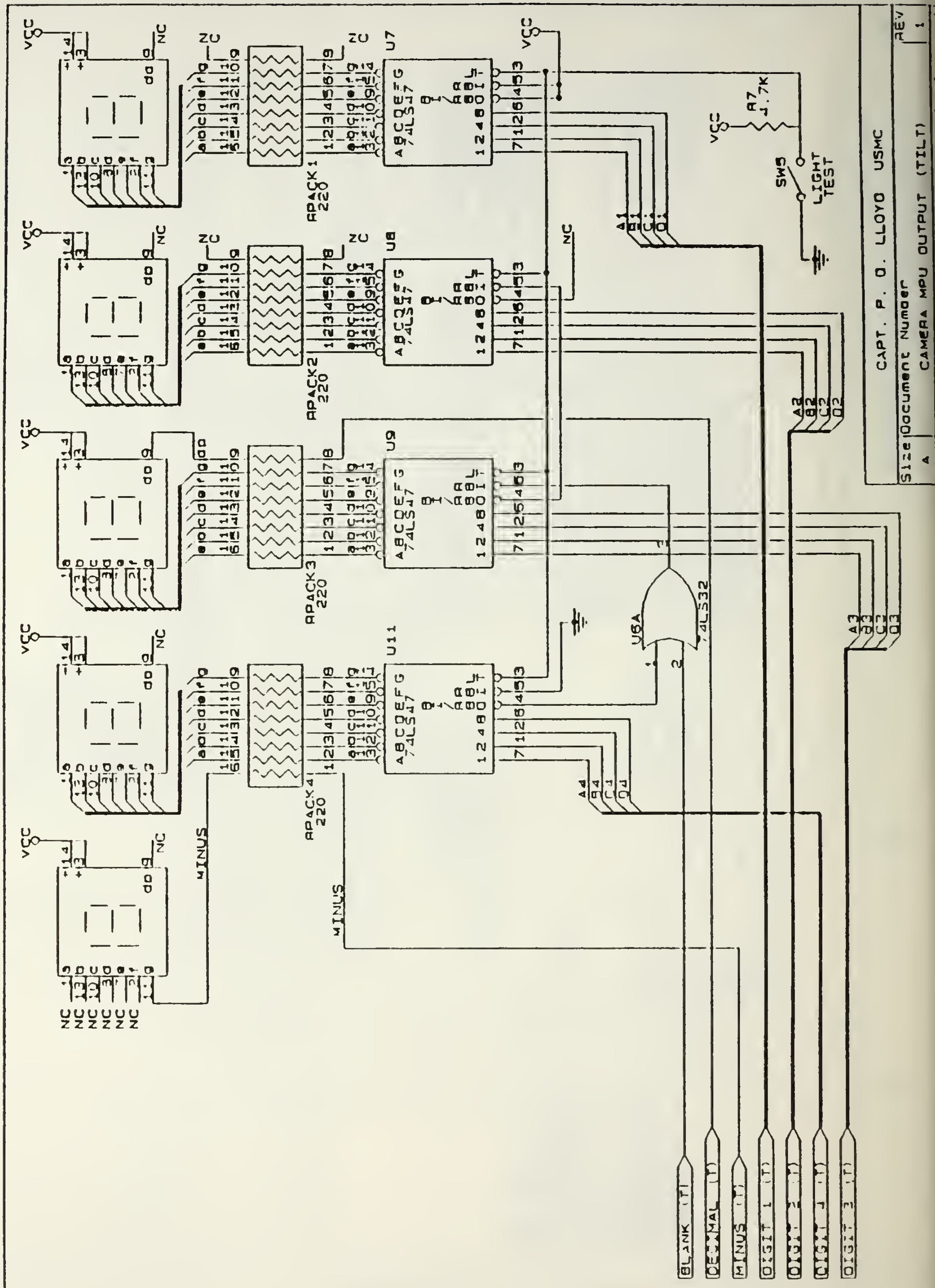
CLOCK
C3
1 uF
VCC
X1
EX2
RESET
INT
TIMER
VPP
PB0
PB1
PB2
PB3
PB4
PB5
PB6
PB7
PC0
PC1
PC2
PC3
PC4
PC5
PC6
PC7
PD0
PD1
PD2
PD3
PD4
PD5
PD6/INT2
PD7
PA0
PA1
PA2
PA3
PA4
PA5
PA6
PA7
BLANK (T)
MINUS (T)
DECIMAL (T)
RESET (T)
INTERRUPT (T)
MODE (T)
FUNCTION (T)


CAPT. P. D. LLOYD USMC
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Document Number
CAMERA MPU OUTPUT (TILT)
REV
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U11
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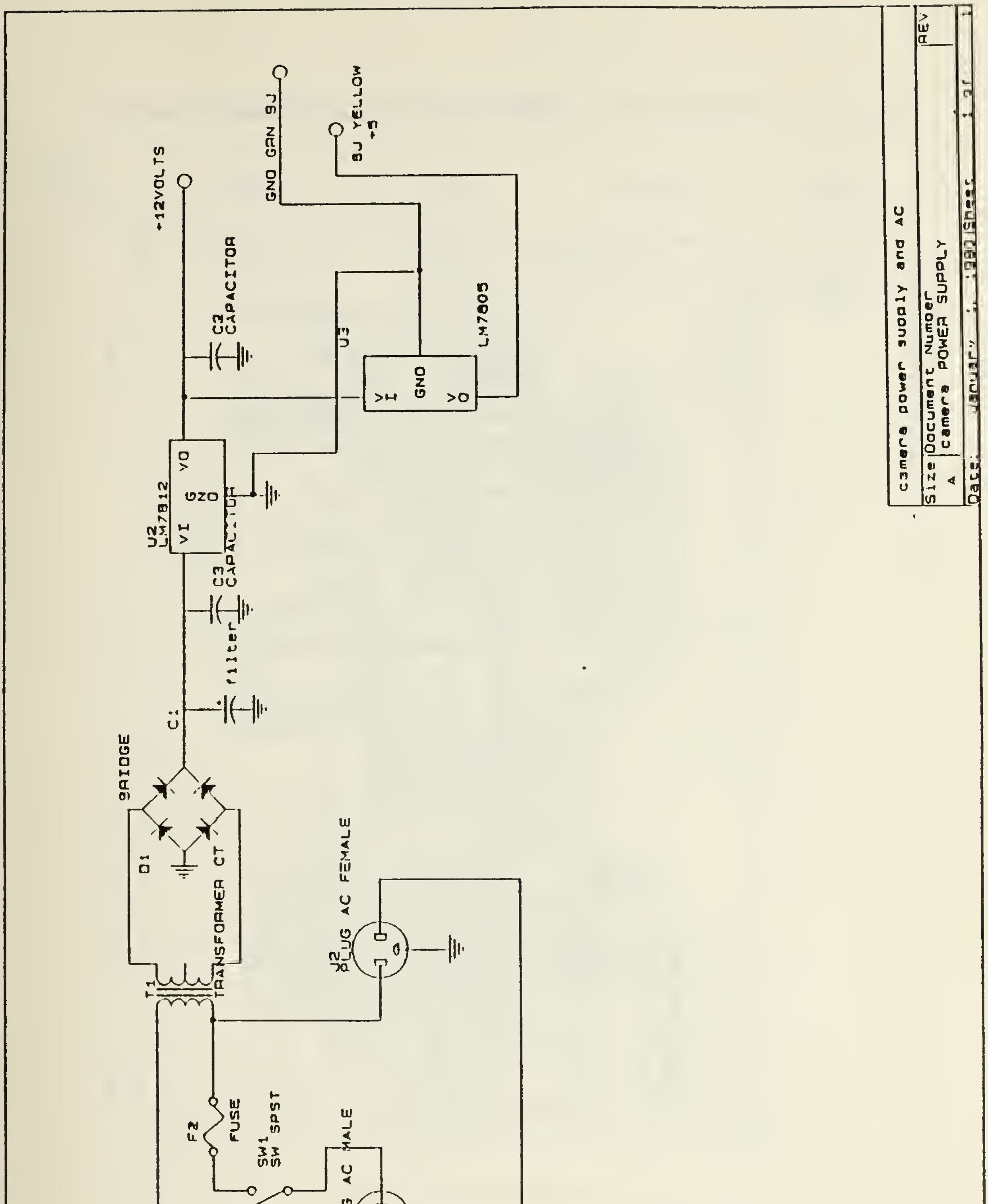
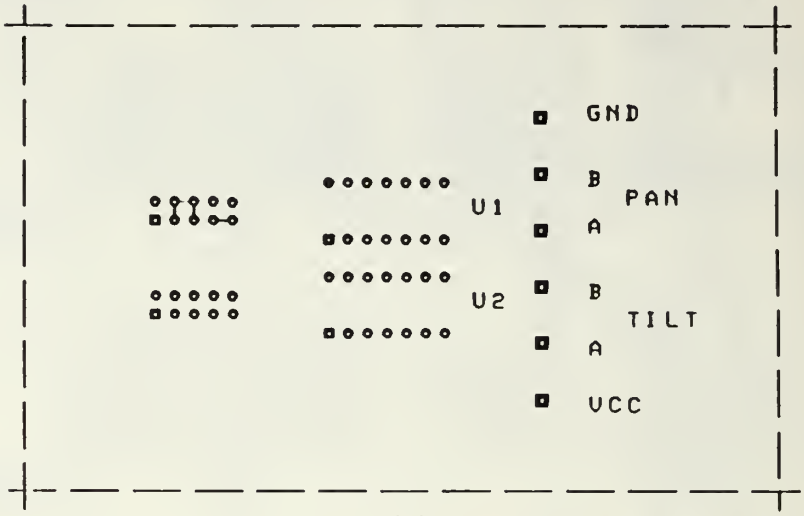
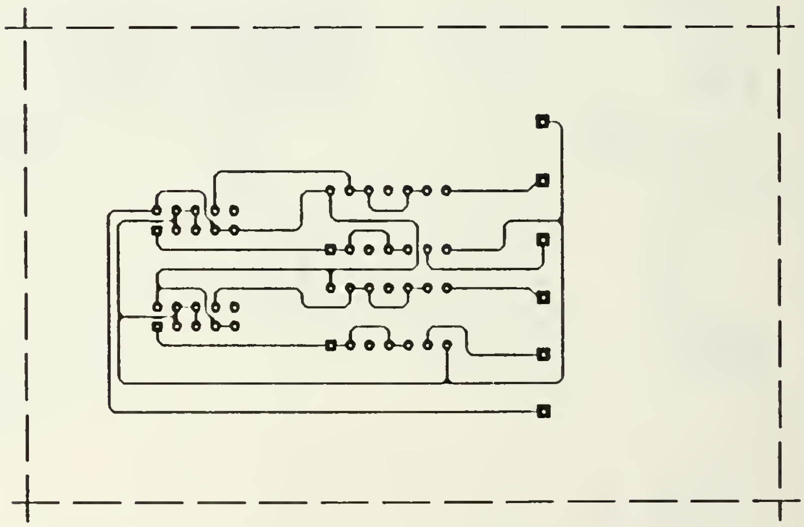
RPACK3
220
RPACK4
220
U6A
74LS32
R7
4.7K
SW5
LIGHT TEST
VCC
NC
MINUS
BLANK (T)
MINUS (T)
DIGIT 1 (T)


+12VOLTS
GND GRN 9J
9J YELLOW
+5
C2
CAPACITOR
U3
LM7805
VI
GND
VO
U2
LM7812
VI
GND
VO
C3
CAPACITOR
filter
C1
9RIDGE
D1
TRANSFORMER CT
T1
J2
PLUG AC FEMALE
F1
FUSE
SW1
SW SPST
J1
PLUG AC MALE
camera power supply and AC
Size
A
Document Number
camera POWER SUPPLY
REV
Date:
Sheet

APPENDIX B. PRINTED CIRCUIT BOARD PLANS

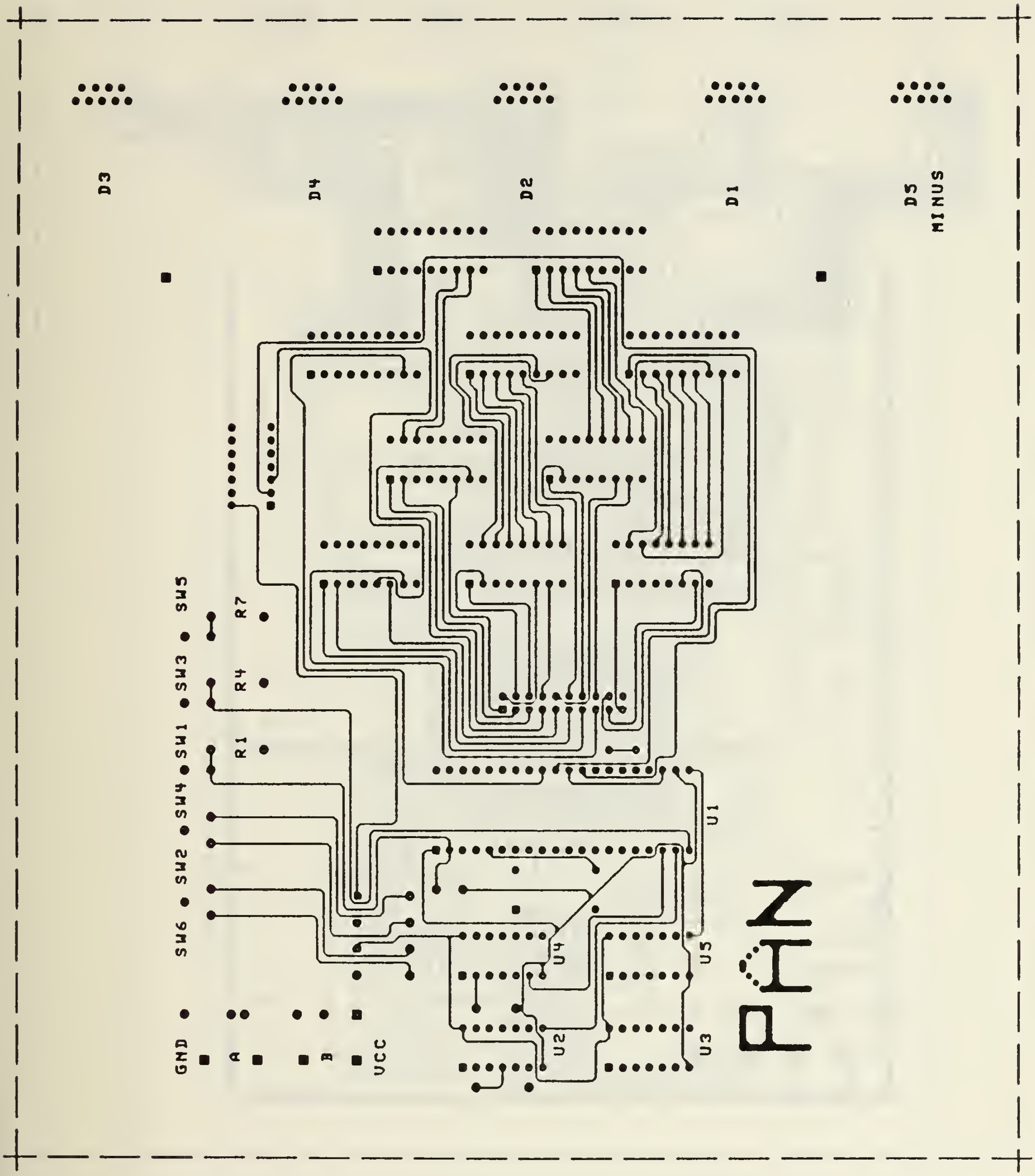


(a)

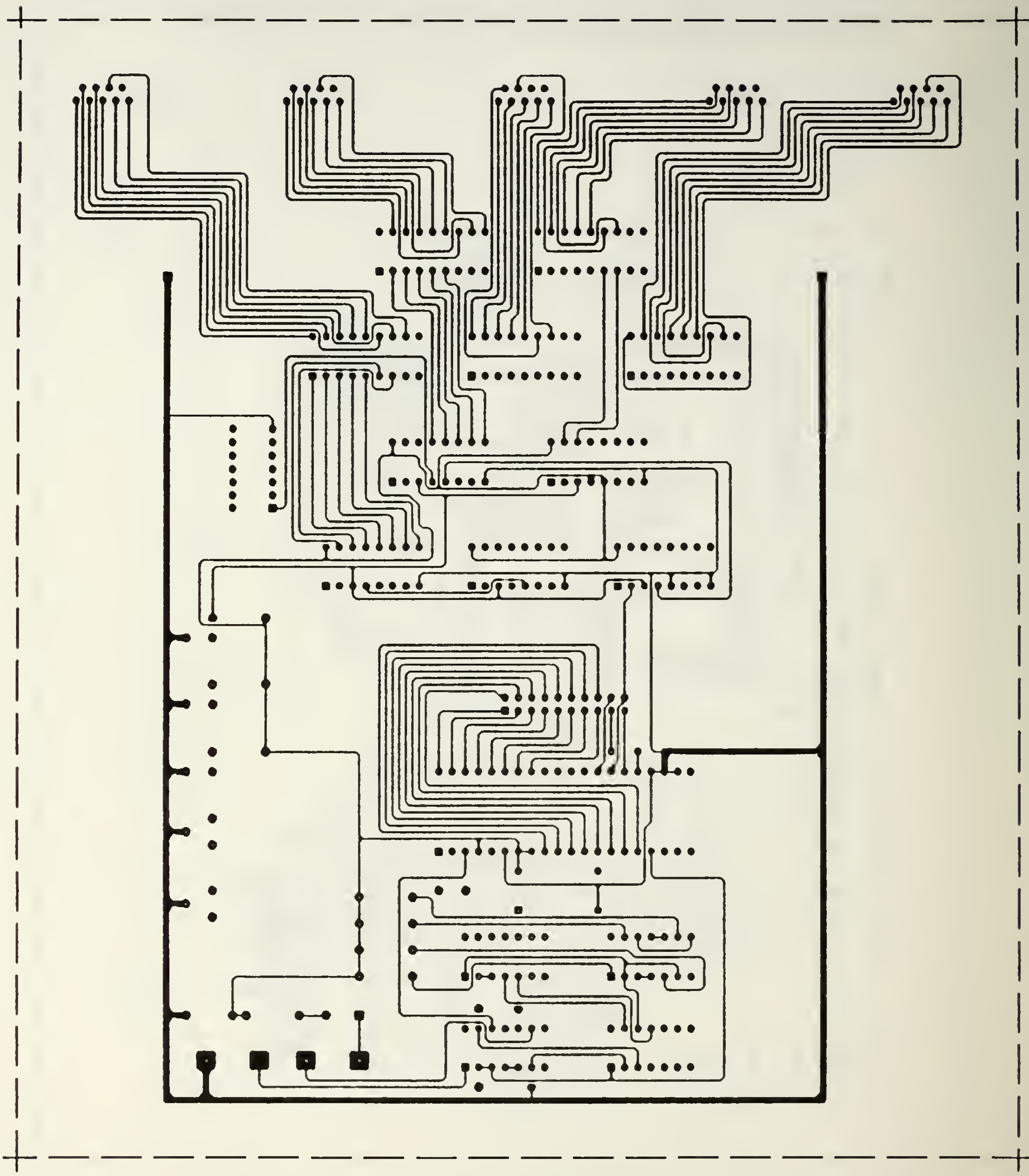


(b)

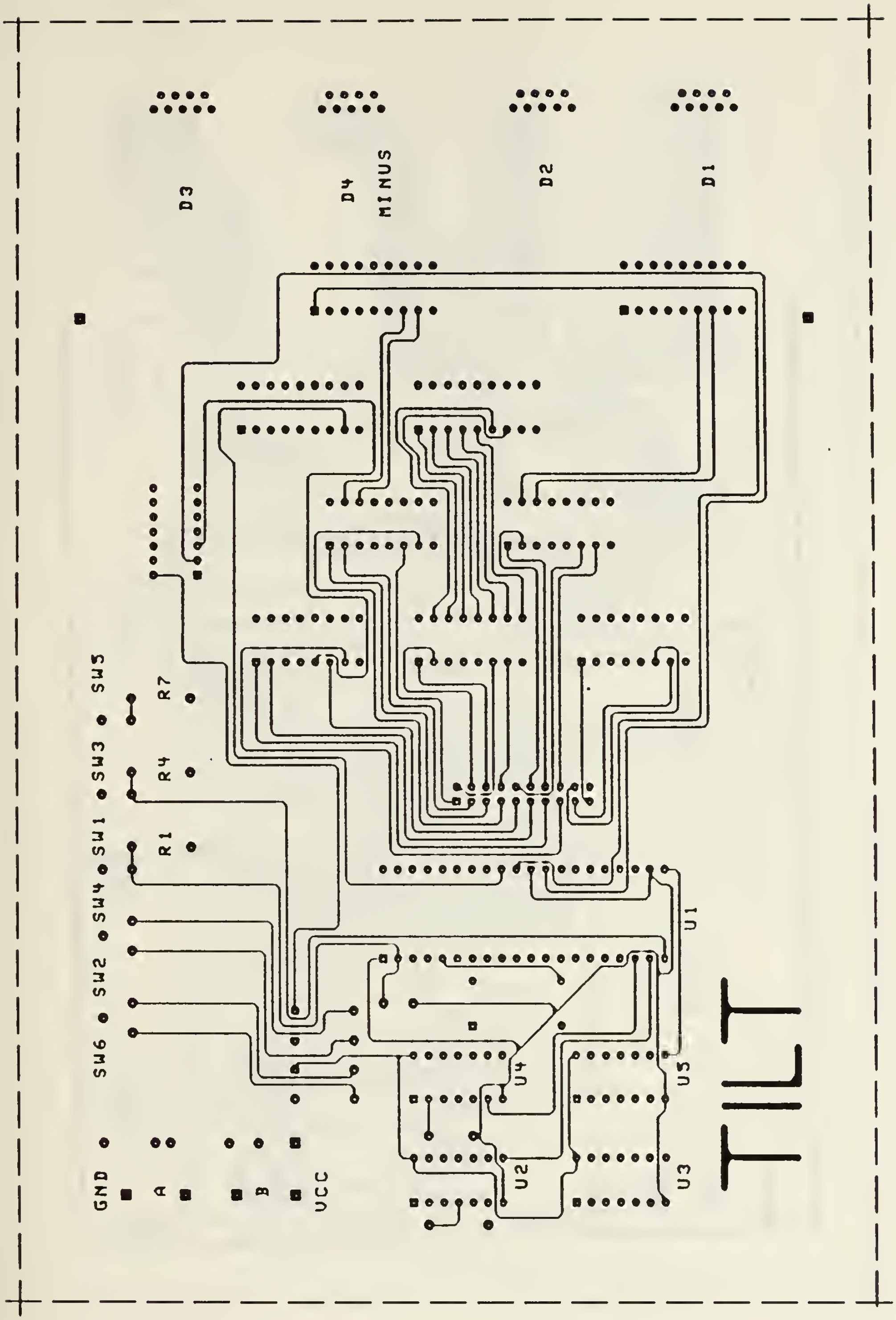
Line Driver, (a) Front and (b) Back. Full scale.



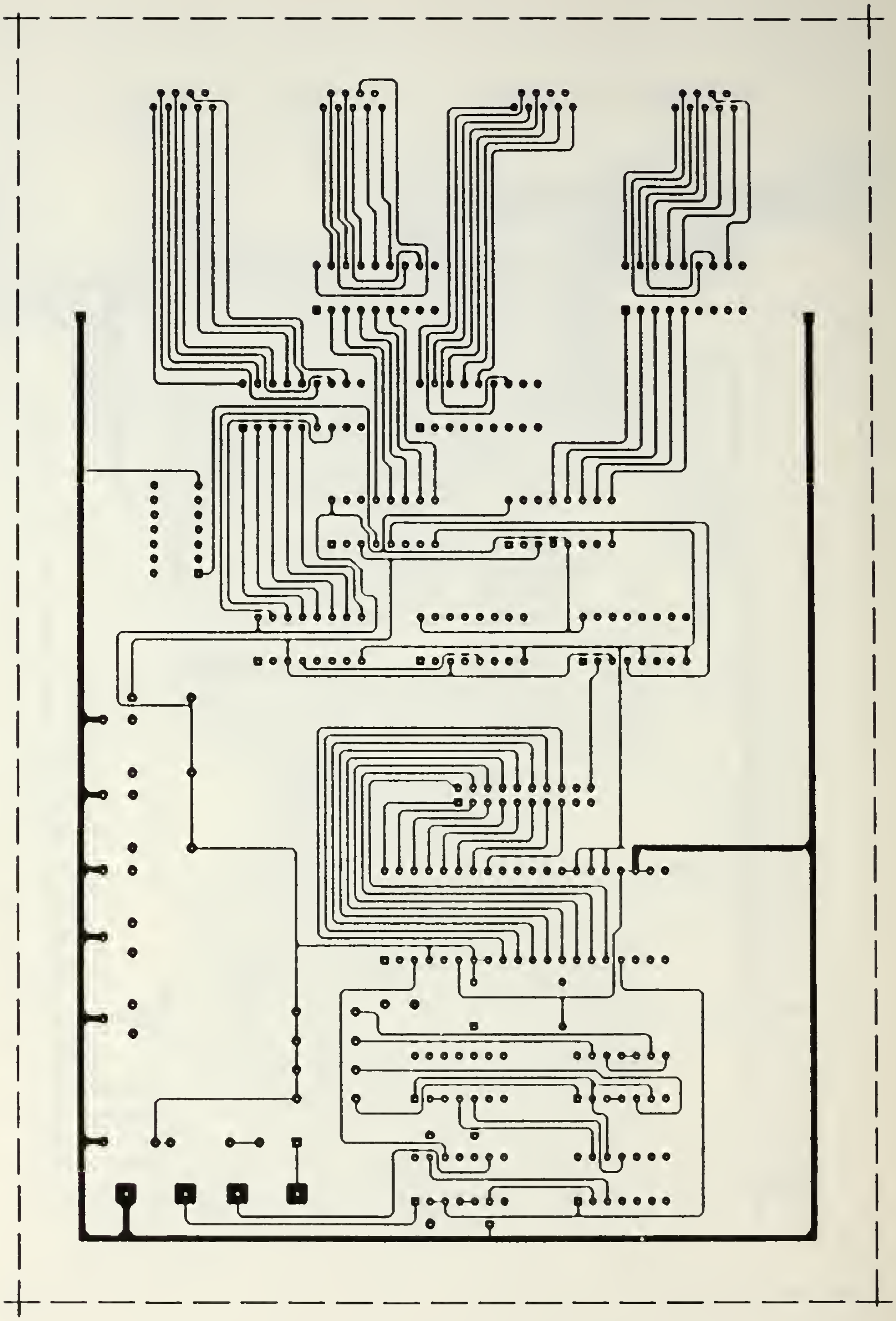
Pan MPU, Front. 90 % of full scale.



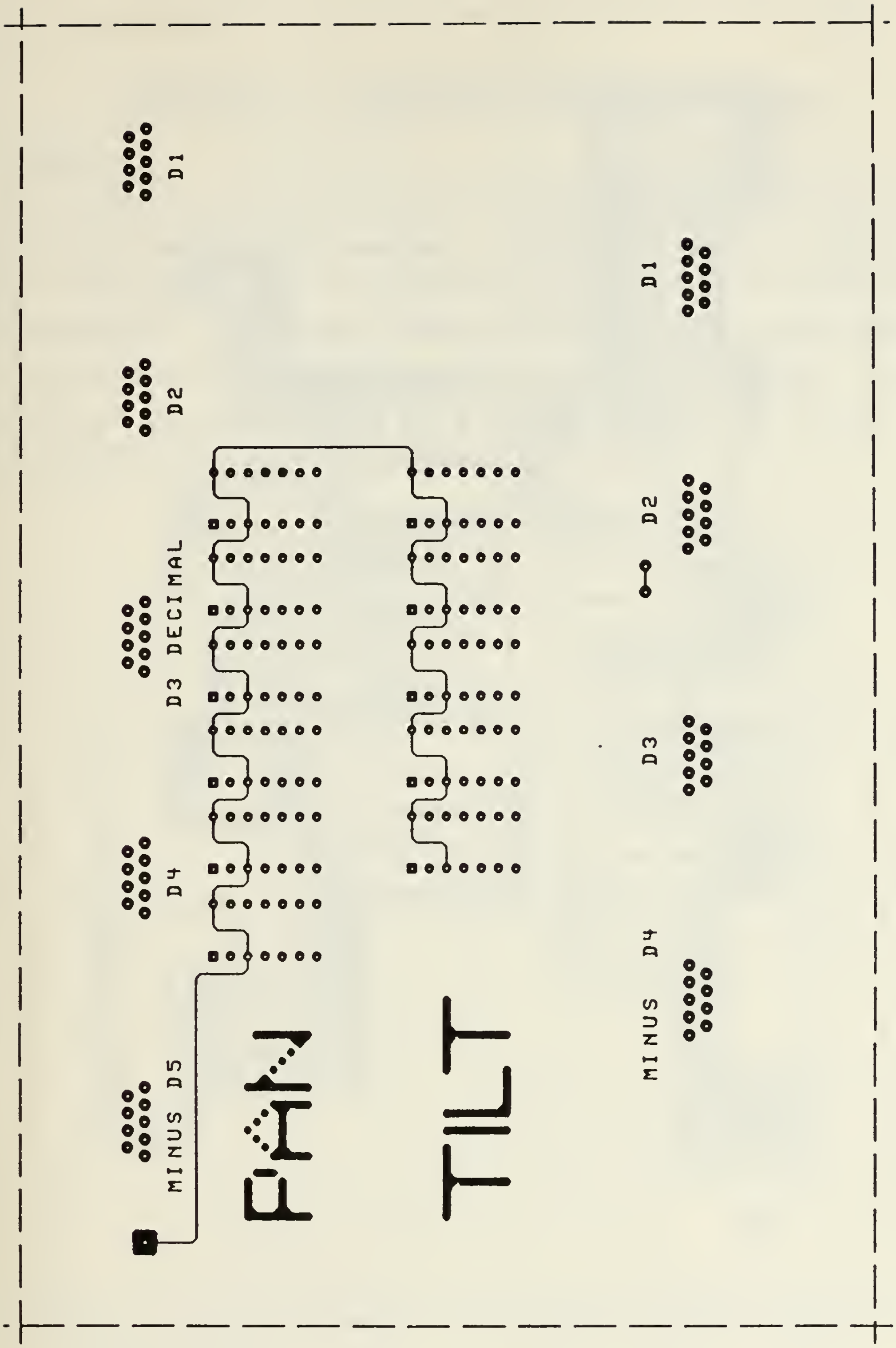
Pan MPU, Back. 90 % of full scale.



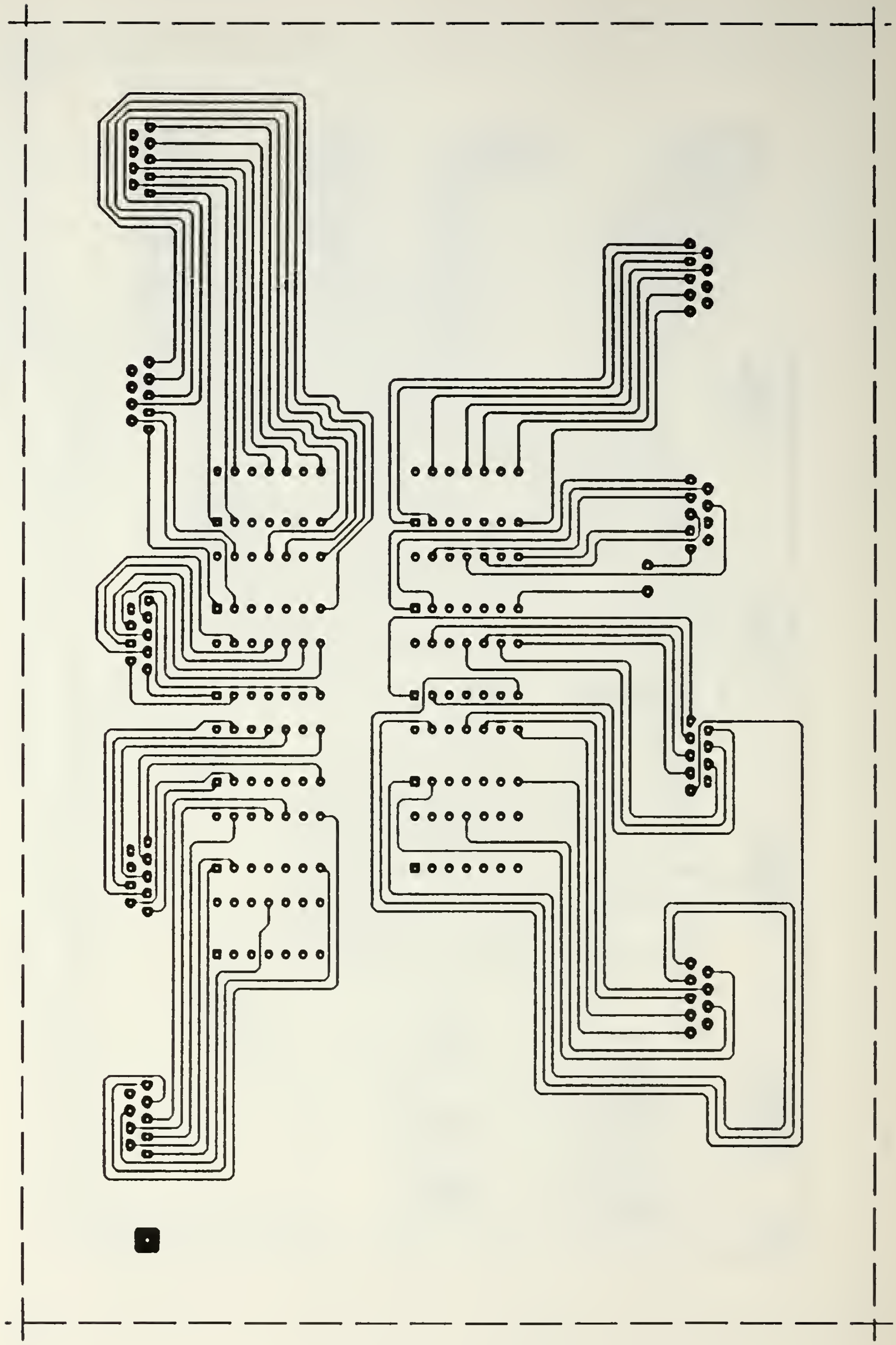
Tilt MPU, Front. 85 % of full scale.



Tilt MPU, Back. 85 % of full scale.



Display, Front. Full scale.



Display, Back. Full scale.

APPENDIX C. MICROPROCESSOR PROGRAMS

A. GENERAL

Sections B and C of this Appendix are the listing files for the two MPU programs written for the signal processor subsystems. The theory of operation of the two programs is identical and is most clearly described by Figure 31. The detailed operation of the Initialization , Mode Change, Blink, Output Display and Hysteresis Modify routines is described by the comments which accompany each of the programs. In addition to the detailed description provided by the program comments, the operation of the Count Routine is also explained in Chapter IV.

B. PAN

```
                         TTL           POSITION DETERMINING PROGRAM (AZIMUTH)
                *                      LATEST REVISION            9 MAY 89
                *                      FILE NAME                  PAN.ASM
                **
                ** PROGRAM DESCRIPTION
                **
                **
                **
                ** I/O REGISTER ADDRESSES
                **
     0000       PORTA   EQU     $0000   I/O PORT A
     0001       PORTB   EQU     $0001   I/O PORT B
     0002       PORTC   EQU     $0002   I/O PORT C
     0003       PORTD   EQU     $0003   INPUT PORT D
                **
                ** DATA DIRECTION REGISTER OFFSET
                **
     0004       DDR     EQU     4       (eg. DDR FOR PORT A IS  PORTA+DDR )
                **
                ** OTHERS
                **
     0008       TIMER   EQU     $0008   EIGHT BIT TIMER REGISTER.
     0009       TCR     EQU     $0009   TIMER CONTROL REGISTER.
     000A       MR      EQU     $000A   MISCELLANEOUS REGISTER.
     0010       RAM     EQU     $0010   START OF ON-CHIP RAM(112 - 31 FOR STACK)
     0080       ZROM    EQU     $0080   PAGE ZERO OF ROM.
     0100       ROM     EQU     $0100   START OF MAIN ROM.
     0F38       MOR     EQU     $0F38   MASK OPTION REGISTER.
     0FF8       INTRPT  EQU     $0FF8   LOCATION OF INTERRUPT VECTORS.
     1000       MEMSIZ  EQU     $1000   MEMORY ADDRESS SIZE.
                **
                ** EQUATES
                **
     0001       BIT0    EQU     1
     0002       BIT1    EQU     2
     0004       BIT2    EQU     4
     0008       BIT3    EQU     8
     0010       BIT4    EQU     16
     0020       BIT5    EQU     32
     0040       BIT6    EQU     64
     0080       BIT7    EQU     128
                **
     0000       B0      EQU     0
     0001       B1      EQU     1
     0002       B2      EQU     2
     0003       B3      EQU     3
     0004       B4      EQU     4
     0005       B5      EQU     5
     0006       B6      EQU     6
     0007       B7      EQU     7
                **
                ** EQUATES FOR THE TIMER CONTROL REGISTER
                **
                ***
     0007       TIR     EQU     7       TIMER INTERRUPT REQUEST. 1 = REQUEST, 0 = NO REQ.
     0006       TIM     EQU     6       TIMER INTERRUPT MASK. 1 = DISABLED, 0 = ENABLED.
     0005       TIN     EQU     5       EXTERNAL OR INTERNAL CLOCK SOURCE. 1 = EXT, 0 = INT
     0004       TEE     EQU     4       EXTERNAL CLOCK ENABLE. NOT USED.
     0003       PSC     EQU     3       PRESCALER CLEAR. NOT USED.
     0002       PS2     EQU     2       (PS2)  --
     0001       PS1     EQU     1       (PS1)    |--  PRESCALER SELECT BITS.
```

```
     0000        PS0     EQU     0       (PS0)  --
                 **
                 ** EQUATES FOR THE STATUS BYTE, 'STAT'.
                 ***
                 ***
                 **
     0007        UD      EQU     7       COUNT DIRECTION?  1 = UP, 0 = DOWN.
     0006        MOD_32  EQU     6       IS 'BINCT' MODULO 32?   1 = YES, 0 = NO.
     0005        FLASH   EQU     5       BLINK THE DISPLAY?  1 = YES, 0 = NO.
     0004        POSCT   EQU     4       DISPLAY POSITION OR COUNT?  1 = POS, 0 = COUNT.
     0003        L_SET   EQU     3       VALUE OF 'MODE,PORTD' LAST TIME.
     0002        NEGTIV  EQU     2       IS 'BCDCT'NEGATIVE NUMBER?  1 = YES, 0 = NO.
                 ***             1       NOT USED.
                 ***             0       NOT USED.
                 ***
                 ***
                 ** I/O EQUATES AND DESCRIPTIONS.
                 ***
                 ***
                 ***      PORT A  (I/O)
                 ***
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***     |          BCD DIGIT #4         |          BCD DIGIT #3         |
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***     |  D4   |  C4   |  B4   |  A4   |  D3   |  C3   |  B3   |  A3   |
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 *** BIT     7       6       5       4       3       2       1       0
                 ***
                 ***
                 ***      PORT B  (I/O)
                 ***
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***     |        DISPLAY CONTROL .      |BCD DIGIT #5 (MOST SIGNIFICANT)|
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***     | DECPT | POSTIV|       | BLANK |  D5   |  C5   |  B5   |  A5   |
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 *** BIT     7       6       5       4       3       2       1       0
                 ***
     0007        DECPT   EQU     7       TO DISPLAY THE DECIMAL POINT...DECPT IS CLEARED
     0006        POSTIV  EQU     6       USED TO DISPLAY NEGATIVE SIGN...CLEARED TO SHOW
                 ***                     MINUS SIGN.
     0004        BLANK   EQU     4       TO BLANK DIGITS 2 AND 3...CLEAR BLANK.
                 ***                     DIGITS 4 AND 5 ARE ALWAYS BLANKED.
                 ***                     DIGIT 1 IS NEVER BLANKED.
                 ***
                 ***      PORT C  (I/O)
                 ***
                 ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***     |          BCD DIGIT #2         |BCD DIGIT #1(LEAST SIGNIFICANT)|
                 ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                 ***     |  D2   |  C2   |  B2   |  A2   |  D1   |  C1   |  B1   |  A1   |
                 ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                 *** BIT     7       6       5       4       3       2       1       0
                 ***
                 ***
                 ***      PORT D  (INPUT ONLY)
                 ***
                 ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                 ***     | CH_A  | INT2  | CH_B  | FUNCT |  SET  |       |       |       |
                 ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                 *** BIT     7       6       5       4       3       2       1       0
                 ***
     0007        CH_A    EQU     7       INDICATES THE STATUS OF CHANNEL A.
     0006        INT2    EQU     6       INTERRUPT #2.  USED TO CHANGE DISPLAY MODES.
     0005        CH_B    EQU     5       INDICATES THE STATUS OF CHANNEL B.
     0004        FUNCT   EQU     4       USED TO PUT THE PROGRAM IN A MODE THAT WILL ALLOW
```

```
                    ***                     'HYST' TO BE INCREMENTED.
        0003        SET     EQU    3        INCREMENTS 'HYST' WHEN TOGGLED AND FUNCT IS LOW.
                    ***
                    ***
                    ****************************************************************************
                    **                                                                         *
                    **                          RAM VARIABLES                                  *
                    **                                                                         *
                    ****************************************************************************
                    **
                    ** RESERVE MEMORY SPACE FOR THE PROGRAM VARIABLES.
                    **
0000                        DATA
                    **
                    **
0000                        ABSOLUTE (ABSOLUTE ADDRESSING USED HERE TO RELATIVE DIRECTIVE)
                    **
0010                        ORG     RAM      START OF RAM.
                    **
                    *** BINARY COUNT.
0010                BINCT   RMB     3
        0010        HIBIN   EQU     BINCT    HI BYTE.
        0011        MIDBIN  EQU     BINCT+1  MIDDLE BYTE.
        0012        LOBIN   EQU     BINCT+2  LO BYTE.
                    **
                    *** POSITION POINTERS.
0013                PTR     RMB     4        EACH BYTE POINTS TO A POSITION IN THE
                    **                       TABLE THAT CONTAINS ONE OR TWO DIGITS
                    **                       OF THE BCD POSITION.
        0013        PTR4    EQU       PTR    MOST SIGNIFICANT DIGITS.
        0014        PTR3    EQU       PTR+1
        0015        PTR2    EQU       PTR+2
        0016        PTR1    EQU       PTR+3  LEAST SIGNIFICANT DIGIT.
                    **
                    *** COUNT POINTERS.
0017                CTPTR   RMB     3        EACH BYTE POINTS TO A POSITION IN THE
                    **                       TABLE THAT CONTAINS TWO OF THE DIGITS
                    **                       IN THE BCD COUNT.
        0017        CTPTR3  EQU     CTPTR    MOST SIGNIFICANT DIGITS.
        0018        CTPTR2  EQU     CTPTR+1
        0019        CTPTR1  EQU     CTPTR+2  LEAST SIGNIFICANT DIGITS.
                    **
                    *** BCD POSITION IN DEGREES.
001A                DEGRES  RMB     4
        001A        HUNDEG  EQU     DEGRES         CONTENTS X 100.000
        001B        ONEDEG  EQU     DEGRES+1       CONTENTS X   1.000
        001C        HUNDTH  EQU     DEGRES+2       CONTENTS X   0.010
        001D        THOUTH  EQU     DEGRES+3     + CONTENTS X   0.001
                    ***                          ---------------------
                    ***                            POSITION IN DEGREES
                    **
                    *** BCD COUNT.
001E                BCDCT   RMB     3
        001E        TENTHO  EQU     BCDCT          CONTENTS X 10,000
        001F        HUNDRD  EQU     BCDCT+1        CONTENTS X    100
        0020        TENONE  EQU     BCDCT+2      + CONTENTS X      1
                    ***                        -------------------------
                    ***                        NUMBER OF PULSES COUNTED
                    ***
                    *** HYSTERESIS COUNTER. POINTS TO A NUMBER IN THE TABLE THAT IS THE
                    ***      AMOUNT OF HYSTERESIS PRESENT IN THE SYSTEM.  INITIALIZED TO 7.
0021                HYSTPT  RMB      1
                    **
                    *** POSITION INCREMENT.  CONTAINS A NUMBER, THAT WHEN MULTIPLIED BY 0.001
                    ***      IS THE NUMBER OF DEGREES THAT THE POSITION COUNTER (BCDPOS) IS
                    ***      TO BE INCREMENTED OR DECREMENTED DURING PROGRAM EXECUTION.
```

```
                   ***      THE VALUE OF 'POSINC', DETERMINED EXPERIMENTALLY, SHOULD BE
                   ***      7.0312.  SINCE THE PROGRAM IS DESIGNED WORK WITH INTEGERS ONLY
                   ***      THIS NUMBER IS ROUNDED TO 7.  TO REDUCE THE CUMULATIVE EFFECT OF
                   ***      THE ROUND OFF, EVERY 32 COUNTS 'POSINC' IS SET EQUAL TO 8.  THIS
                   ***      AGAIN LEADS TO SOME CUMULATIVE ERROR THAT IS ACCOUNTED FOR BY
                   ***      SETTING 'POSINC' TO 7 INSTEAD OF 8 WHEN THE COUNT REACHES A
                   ***      VALUE OF 16384 (2^14).
                   ***
0022               POSINC  RMB     1
                   ***
                   *** HYSTERESIS VARIABLES.  USED TO ELIMINATE THE EFFECTS OF BACKLASH ON
                   ***      THE POSITION MEASUREMENTS.
                   ***
0023               HYST    RMB     1       THE THRESHHOLD VALUE DETERMINED
                   ***                     EXPERIMENTALLY.
0024               HYSTCT  RMB     1       CURRENT AMOUNT OF HYSTERESIS MEASURED.
                   ***
                   *** STATUS BYTE.  USED TO KEEP TRACK OF WHAT IS GOING ON.
                   ***
0025               STAT    RMB     1       CURRENT STATUS.
0026               LSTAT   RMB     1       PREVIOUS/LAST STATUS.  USED TO KEEP TRACK OF
                   ***                     L_SET ONLY.
                   ***
                   *** TIMER COUNTER.  USED IN CONJUNCTION WITH THE TIMER PRESCALER AND THE
                   ***      TDR TO KEEP TRACK OF ONE SEC. INTERVALS.  USED IN BLINKING THE
                   ***      DISPLAY.  INITIALLY SET TO 31, WHEN THE 'FLASH' BIT OF 'STAT'
                   ***      IS SET.  TIMCT IS DECREMENTED EACH CLOCK INTERRUPT (APPROX. 31
                   ***      TIMES PER SEC).  RESET TO 31 WHEN CONTENTS GO TO ZERO.
                   ***      WHEN (TIMCT)=0 THE DISPLAY WILL TOGGLE.
                   ***
0027               TIMCT   RMB     1
                   **
                           ENDS
                   **
                   ***
                   ********************************************************************************
                   **                                                                            *
                   **                               PAGE ZERO ROM
                   **                                                                            *
                   ********************************************************************************
                   **
                   **                          INITIALIZATION ROUTINE.
                   **
                   **
0000                       CODE
                   **
0080                       ORG     ZROM    PAGE ZERO ROM.
                   **
0080                       RELATIVE        RELATIVE ADDRESSING MUST BE USED FOR THE BRANCH.
                   **
      0080         RESTRT  EQU     $       THIS IS THE ENTRY POINT WHEN THE RESET
                   ***                     SWITCH IS PUSHED.
                   **
                   ********************************************************************************
                   **
                   ***                INITIALIZE THE PC AND CLEAR RAM.
                   ***
                   ***
0080  9B                   SEI             SET INTERUPT TO AVOID INTERUPTION AND
0081  9C                   RSP             RESET THE STACK POINTER. JUST IN CASE!
                   ***
0082  AE 10                LDX     #BINCT  CLEAR ALL OF THE VARIABLES BETWEEN
0084  7F           CLRIT   CLR     ,X      'BINCT' AND 'TIMCT' (INCLUSIVE).NOTE
0085  5C                   INCX            THAT THIS SETS THE COUNTER AND THE POS-
0086  A3 27                CPX     #TIMCT  ITION TO ZERO. THIS MEANS THAT ROTATION
0088  23 FA                BLS     CLRIT   SHOULD START IN AN INCREASING (CW)
```

```
                               ***                DIRECTION FROM THE MOST CCW POSITION
                               ***                AFTER A RESET.
                               ***
008A                                ABSOLUTE      BACK TO ABSOLUTE ADDRESSING.
                               ***
                               *************************************************************************
                               ***
                               ***                    ESTABLISH I/O PORTS.
                               ***
008A    A6 FF                       LDA     #-1         PORTS A,B,C ARE CONFIGURED AS
008C    B7 04                       STA     PORTA+DDR   ALL OUTPUT. PORT D IS ALL INPUT
008E    B7 05                       STA     PORTB+DDR   SO THERE IS NO MASK TO SET.
0090    B7 06                       STA     PORTC+DDR
                               ***
                               ***
0092    CD 03 4E                    JSR     OUTCT        COUNT IS TO BE DISPLAYED INITIALLY.
                               ***
                               *************************************************************************
                               ***              SET UP THE STATUS REGISTER.
                               ***
0095    A6 08                       LDA     #%00001000   --
0097    B4 03                       AND     PORTD          |--> SET UP 'L_SET' BIT OF 'STAT'.
0099    B7 25                       STA     STAT         --
                               ***
009B    1C 25                       BSET    MOD_32,STAT  0 IS MODULO 32.
                               **
                               *************************************************************************
                               ***
                               ***                  INITIALIZE HYSTCT.
                               ***
009D    A6 08                       LDA     #08
009F    B7 23                       STA     HYST
00A1    B7 21                       STA     HYSTPT
                               ***
                               *************************************************************************
                               **
                               **      SET UP THE TIMER FOR A 4 MHZ CRYSTAL / 4 = 1 MHZ CLOCK.
                               ***
                               ***    NOTE:  THE MASK OPTION REGISTER IS IN ROM.  IT IS SET UP AT
                               ***           THE END OF THE PROGRAM.
                               ***
                               *********************  SET UP THE TCR.  *********************************
                               ***
00A3    A6 47                       LDA       #BIT6+BIT2+BIT1+BIT0
                               ***              (TIM)|(PS2)(PS1)(PS0)
                               ***(DISABLE INTERRUPT)|(PRESCALE BY 128)
                               ***
00A5    B7 09                       STA     TCR
                               ***
                               ***
                               *** SET UP THE TIMER.
                               ***
00A7    A6 FF                       LDA     #255    1 MHZ/(128*255) = 30.6 (APPROX. 31)
00A9    B7 08                       STA TIMER
                               ***
                               ****************  INITIALIZE THE TIMER COUNTER.  ***********************
                               ***
00AB    A6 1F                       LDA     #31     PROVIDES FOR 1 SEC. BLINK INTERVAL.
00AD    B7 27                       STA     TIMCT   FOR 2 SEC. INTERVAL JUST USE TIMECT=62, etc.
                               ***
                               ***
                               ************************************************************************
                               **
                               **                 SET UP MISCELLANEOUS REGISTER.
                               **
00AF    1D 0A                      BCLR    B6,MR   ENABLES THE SECOND INTERRUPT.
```

```
                       **
                       **
00B1  9A                      CLI               CLEAR THE INTERRUPT MASK TO GET STARTED.
                       ***
00B2                          RELATIVE          RELATIVE ADDRESSING MUST BE USED FOR THE
                       ***                      REMAINDER OF THE PROGRAM.
                       ***
                       ******************************************************************************
                       **
                       ** WAIT LOOP.  EXECUTES, UNTIL AN INTERRUPT OCCURS.
                       **
00B2  09 03 0B         PAUSE  BRCLR  FUNCT,PORTD,CHHYST WANT TO CHANGE HYST?
                       **                              YES...GO TO CHHYST.
00B5  06 03 04                BRSET  SET,PORTD,SBIT    NO...'SET,PORTD' SET?
00B8  17 25                   BCLR   L_SET,STAT              NO...CLEAR 'L_SET,STAT'
00BA  20 F6                   BRA    PAUSE                   AND LOOP.
00BC  16 25            SBIT   BSET   L_SET,STAT              YES...SET 'L_SET,STAT'
00BE  20 F2                   BRA    PAUSE                   AND...LOOP
                       **
                       ******************************************************************************
                       **
                       ** HYSTERESIS MODIFICATION ROUTINE.  PERMITS MODIFICATION OF THE
                       ** HYSTERESIS BUFFER WITHOUT REPROGRAMMING.
                       **
00C0  A6 40            CHHYST LDA    #BIT6              DISABLE TIMER INTERRUPT.
00C2  B7 09                   STA    TCR
                       ***
00C4  A6 08                   LDA    #%00001000         SAVE 'L_SET'
00C6  B4 25                   AND    STAT               INTO
00C8  B7 26                   STA    LSTAT              'LSTAT'.
00CA  A6 08                   LDA    #%00001000
00CC  B4 03                   AND    PORTD              'SET,PORTD' --> ACCUMULATOR
00CE  B1 26                   CMP    LSTAT              HAS THE SET SWITCH BEEN CHANGED?
00D0  27 15                   BEQ    DISPLA
                       ***                              YES...
00D2  A6 08                   LDA    #%00001000         --
00D4  B8 25                   EOR    STAT                 |-->CHANGE 'L_SET,STAT',
00D6  B7 25                   STA    STAT               --
00D8  3C 23                   INC    HYST               THEN INCREMENT THE HYSTERESIS
00DA  3C 21                   INC    HYSTPT             POINTER AND 'HYST'...
                       ***
00DC  B6 21                   LDA    HYSTPT           --
00DE  A1 19                   CMP    #25                --
00E0  23 05                   BLS    DISPLA               --
                       ***                                  -- BUT NOT ABOVE 25.
00E2  4F                      CLRA                        --        THEN--->|
00E3  B7 23                   STA    HYST               --                  |
00E5  B7 21                   STA    HYSTPT           --                    |
                       ***                                                  |
00E7  A6 00            DISPLA LDA    #%00000000         NO... JUST--------->|
00E9  B7 00                   STA    PORTA            --                    |
00EB  A6 C0                   LDA    #%11000000         --                  |
00ED  B7 01                   STA    PORTB                --               \|/
                       ***                                   -- DISPLAY CURRENT 'HYST'.
00EF  BE 21                   LDX    HYSTPT               --
00F1  D6 03 BE                LDA    TABLE,X            --
00F4  B7 02                   STA    PORTC            --
                       ***                              IS 'HYST' SETTING COMPLETE?
00F6  09 03 C7                BRCLR  FUNCT,PORTD,CHHYST NO... KEEP CHECKING 'SET'.
00F9  08 25 05                BRSET  POSCT,STAT,SHOPOS  YES... RESET THE DISPLAY.
00FC  CD 03 4E                JSR    OUTCT
00FF  20 03                   BRA    DUNCHG
                       ***
0101  CD 03 68         SHOPOS JSR    OUTPOS
                       ***
0104  0B 25 04         DUNCHG BRCLR  FLASH,STAT,NO_INT  IF THE DISPLAY IS TO BLINK...
```

```
0107  A6 07              LDA    #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
0109  B7 09              STA    TCR                TIMER PRESCALER
010B  20 A5      NO_INT  BRA    PAUSE              PRIOR TO RETURNING.
                 ***
                 **
                 ***********************************************************************
                 ** MAXIMUM EXECUTION TIME FOR THE REMAINDER OF THE PROGRAM OCCURS
                 ** IF THE COUNTER ROTATES THROUGH ZERO AS THE DISPLAY MODE IS CHANGED
                 ** FROM THE BLINKING MODE TO THE COUNT MODE AT THE SAME TIME THAT THE
                 ** BLINKING ROUTINE IS CAUSING THE DISPLAY TO TOGGLE TO SHOW THE
                 ** POSITION IN DEGREES.
                 **     MAXIMUM EXECUTION TIME = 140 + 184 + 708 = 1032 CLOCK CYCLES.
                 ***********************************************************************
                 **
                 ** MODE CHANGE ROUTINE.  CHANGES THE DISPLAY MODE FROM
                 **       COUNT -> POSITION -> BLINKING -> COUNT ->....(ETC.)
                 **       MAXIMUM EXECUTION TIME OF 181 CLOCK CYCLES OCCURS WHEN THE
                 **       DISPLAY MODE IS CHANGED FROM DISPLAYING THE COUNT TO DISPLAYING
                 **       THE POSITION (IN DEGREES).
                 **       IF THE DISPLAY IS CHANGED FROM BLINKING TO A COUNT DISPLAY
                 **       EXECUTION TIME IS 140 CLOCK CYCLES.
                 **
010D  1F 0A      CHMODE  BCLR   B7,MR              AVOID REPEATED INTERRUPTS.
                 **
010F  0A 25 10           BRSET  FLASH,STAT,DIS_CT  IF FLASHING, DISPLAY COUNT...
0112  09 25 07           BRCLR  POSCT,STAT,DISPOS  IF SHOWING COUNT, DISPLAY POSITION...
0115  1A 25              BSET   FLASH,STAT         ELSE, BLINK.
                 **
0117  A6 07              LDA    #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
0119  B7 09              STA    TCR                TIMER PRESCALER.
011B  80                 RTI
                 **
011C  18 25      DISPOS  BSET   POSCT,STAT       --
011E  CD 03 68           JSR    OUTPOS             |-- DISPLAY CURRENT POSITION, AND WAIT.
0121  80                 RTI                     --
                 **
0122  A6 47      DIS_CT  LDA    #BIT6+BIT2+BIT1+BIT0  DISABLE TIMER INTERRUPT AND RESET
0124  B7 09              STA    TCR                   TIMER PRESCALER.
0126  19 25              BCLR   POSCT,STAT       --
0128  1B 25              BCLR   FLASH,STAT         |
                 **                                |-- DISPLAY CURRENT COUNT, AND WAIT.
012A  CD 03 4E           JSR    OUTCT              |
012D  80                 RTI                     --
                 **
                 ***********************************************************************
                 **
                 ** BLINK ROUTINE.  INTERRUPT ROUTINE TO CHANGE THE DISPLAY FROM POSITION
                 **       TO COUNT OR VICE VERSA EVERY 31 ST TIMER INTERRUPT IF THE
                 **       'FLASH' BIT OF 'STAT' IS SET.
                 **       MAXIMUM EXECUTION TIME OF 184 CLOCK CYCLES OCCURS WHEN THE
                 **       DISPLAY IS TOGGLED FROM A COUNT DISPLAY TO A POSITION DISPLAY.
                 **
      012E       BLINK   EQU    $
012E  0F 09 DC           BRCLR  TIR,TCR,CHMODE        IF THE INTERRUPT WAS NOT A TIMER
                 **                                   INTERRUPT IT MUST BE FROM INT2.
                 **
0131  1F 09              BCLR   TIR,TCR               AVOID REPEATED TIMER INTERRUPTS.
                 **
0133  3A 27              DEC    TIMCT                 IF THERE HAVE BEEN 31 TIMER
0135  27 01              BEQ    CHGDIS                INTERRUPTS  (1 SEC), IT'S TIME TO
                 **                                   CHANGE THE DISPLAY.
0137  80                 RTI                          OTHERWISE, IT'S BACK TO WORK.
                 **
0138  A6 1F      CHGDIS  LDA    #31                   RESET TIMCT TO 31 (1 SEC. INTERVAL).
013A  B7 27              STA    TIMCT
                 **
```

```
013C  B6 25              LDA    STAT            --
013E  A8 10              EOR    #%00010000       |-- CHANGE 'POSCT' BIT OF 'STAT'.
0140  B7 25              STA    STAT            --
                **
0142  08 25 04           BRSET  POSCT,STAT,POSOUT     DECIDE ON CORRECT DISPLAY.
                **
                ************  CHANGE THE DISPLAY TO SHOW THE COUNT.....  ***************
                **
0145  CD 03 4E           JSR    OUTCT
0148  80                 RTI
                **
                ************  OR HAVE THE DISPLAY SHOW THE POSITION.  *****************
                **
0149  CD 03 68  POSOUT   JSR    OUTPOS
014C  80                 RTI
                **
                ***********************************************************************
                **
                **                        COUNT ROUTINE.
                **       WHEN A COUNT IS RECEIVED THIS IS THE ENTRY POINT .
                **       MAXIMUM EXECUTION TIME OF 708 CLOCK CYCLES OCCURS WHEN THE
                **       COUNTER ROTATES CCW THROUGH ZERO AND THE POSITION (IN DEGREES)
                **       IS BEING DISPLAYED.
                **
                **
                ** CURRENT DIRECTION OF ROTATION IS DETERMINED BY INSPECTING THE STATUS
                ** OF 'CH_A' AND 'CH_B'.  THE FOUR POSSIBILITIES AND THE ASSOCIATED
                ** DIRECTION OF ROTATION ARE AS SHOWN BELOW.  NOTE THAT THIS SCHEME
                ** PREVENTS MULTIPLE OSCILLATIONS ABOUT A SINGLE POINT FROM
                ** REPEATEDLY INCREMENTING OR DECREMENTING THE COUNTER.
                **
                **   +--------+---------+-----------------+------------------+
                **   |  CH_A  |  CH_B   |  DIRECTION      | COUNT THE PULSE? |
                **   |        |         |  OF ROTATION    |                  |
                **   +--------+---------+-----------------+------------------+
                **   |   LO   |   LO    |      CW         |       NO         |
                **   |   LO   |   HI    |      CCW        |       YES        |
                **   |   HI   |   LO    |      CCW        |       NO         |
                **   |   HI   |   HI    |      CW         |       YES        |
                **   +--------+---------+-----------------+------------------+
                **
                ********  FIRST SEE IF WE ARE SUPPOSED TO COUNT THIS INTERUPT.  ********
                **
      014D      COUNT    EQU    $
014D  0A 03 01           BRSET  CH_B,PORTD,OKCT    IF CH_B IS LO WE DON'T COUNT THE
0150  80                 RTI                       INTERRUPT.
                **
                **************  IF THE INTERRUPT IS VALID UPDATE 'STAT'.  **************
                **
0151  A6 7F     OKCT     LDA    #%01111111
0153  B4 25              AND    STAT            SAVE ALL OF THE OLD 'STAT' EXCEPT THE
0155  B7 25              STA    STAT            DIRECTION OF ROTATION.
0157  A6 80              LDA    #%10000000
0159  B4 03              AND    PORTD           'CH_A,PORTD' INDICATES THE DIRECTION
                *                               OF ROTATION AND BECOMES 'UD,STAT'.
015B  BA 25              ORA    STAT            ADD THE RESULTS TO GET
015D  B7 25              STA    STAT            THE NEW 'STAT'.
                **
                ** DECIDE IF THE "SLACK" DUE TO BACKLASH/HYSTERESIS HAS BEEN TAKEN OUT.
                **
015F  0E 25 09           BRSET  UD,STAT,HYSTCK  IF ROTATING CW SEE BELOW.
0162  B6 24              LDA    HYSTCT          ELSE, SEE IF WE DECREMENT THIS TIME.
0164  27 60              BEQ    CCW             IF HYSTCT=0, GO TO THE COUNT DOWN
                **                              ROUTINE.
0166  A0 01              SUB    #1              ELSE, DECREMENT THE HYSTERESIS COUNTER,
0168  B7 24              STA    HYSTCT
```

```
016A   80                   RTI                        AND WAIT FOR THE NEXT INTERRUPT.
                     **
016B   B6 23         HYSTCK LDA     HYST               IF ROTATING CW....
016D   B1 24                CMP     HYSTCT             AND  HYST = HYSTCT ....
016F   27 03                BEQ     CW                 COUNT THE PULSE .
0171   3C 24                INC     HYSTCT             ELSE, INCREMENT THE HYSTERESIS COUNTER,
0173   80                   RTI                        AND WAIT FOR ANOTHER PULSE.
                     **
                     **
                     ************************************************************************
                     **
                     **                          CLOCKWISE ROUTINE.
                     **
       0174          CW     EQU     $
                     **
                     ***
                     ***************  INCREMENT THE BINARY COUNTER (BINCT).  ******************
                     ***
0174   B6 12                LDA     LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
0176   AB 01                ADD     #1      LOBIN = LOBIN + 1 ; CARRY -> C,CCR
0178   B7 12                STA     LOBIN
                     ***
017A   B6 11                LDA     MIDBIN
017C   A9 00                ADC     #0                 ADD THE CARRY TO THE MIDDLE BYTE.
017E   B7 11                STA     MIDBIN
                     ***
0180   B6 10                LDA     HIBIN
0182   A9 00                ADC     #0                 ADD THE CARRY TO THE HIGH BYTE.
0184   B7 10                STA     HIBIN
                     ***
                     ***
                     *******************  CLR/SET MOD_32 APPROPRIATELY.  **********************
                     ***
                     ***    THE FOLLOWING SEVERAL LINES OF CODE ARE PRETTY MESSY.  ALL THAT
                     ***    IS BEING DONE IS TO ENSURE THAT THE SCALE FACTOR IS SET PROPERLY.
                     ***    FOR THE PAN AXIS THE SCALE FACTOR IS;
                     ***
                     ***              1 PULSE => 0.007097 DEGREES
                     ***
0186   B6 12                LDA     LOBIN         IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
0188   A4 1F                AND     #%00011111    ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
018A   26 0F                BNE     NOT_32
018C   B6 11                LDA     MIDBIN        IF THE LOW SIX BITS OF 'MIDBIN' ARE ZERO
018E   27 07                BEQ     MOD           AND 'HIBIN' .NE. ZERO
0190   A4 3F                AND     #%00111111    THEN THE NUMBER IS MODULO 16,384, AND WE
0192   26 03                BNE     MOD           DON'T WANT TO SET 'MOD_32,STAT', UNLESS
0194   0D 11 04             BRCLR   B6,MIDBIN,NOT_32  THE NUMBER IS ALSO MODULO 32,768.
                     ***
0197   1C 25         MOD    BSET    MOD_32,STAT
0199   20 02                BRA     DIRCHK
                     ***
019B   1D 25         NOT_32 BCLR    MOD_32,STAT
                     ***
                     ***
019D   B6 10         DIRCHK LDA     HIBIN
019F   2B 1D                BMI     CWNEG           IF HIBIN < 0 , WE'RE ROTATING CCW TOWARD
                     ***                            THE ORIGIN.
                     ***
01A1   26 14                BNE     CWPOS
01A3   B6 11                LDA     MIDBIN          ELSE IF BINCT .NE. 0
01A5   26 10                BNE     CWPOS           WE'RE ROTATING CW
01A7   B6 12                LDA     LOBIN           AWAY FROM THE ORIGIN.
01A9   26 0C                BNE     CWPOS

                     ***                            ELSE, WE'VE ROTATED CW THROUGH THE ORIGIN.
01AB   15 25                BCLR    NEGTIV,STAT     CLR NEGATIVE SIGN.
```

```
01AD   AE 13               LDX    #PTR4   --
01AF   7F          CLRIT2  CLR    ,X        --
01B0   5C                  INCX               --RESET ALL COUNTERS AND DEGRES TO ZERO.
01B1   A3 1D               CPX    #THOUTH   --
01B3   23 FA               BLS    CLRIT2  --
01B5   20 68               BRA    UPOUT        UPDATE OUTPUT.
                   ***
01B7   AD 74       CWPOS   BSR    ADDBCD
01B9   CD 02 6A            JSR    INCPOS
01BC   20 64               BRA    UPOUT
                   ***
01BE   CD 02 CA    CWNEG   JSR    SUBBCD
01C1   CD 02 6A            JSR    INCPOS
01C4   20 5C               BRA    UPOUT
                   ***
                   **
                   ******************************************************************************
                   **
                   **                    COUNTER-CLOCKWISE ROUTINE.
                   **
       01C6        CCW     EQU    $
                   **
                   ***
                   ******************  CLR/SET MOD_32 APPROPRIATELY.  *********************
                   ***
                   ***     AGAIN SET THE SCALE FACTOR TO;
                   ***
                   ***                 1 PULSE => 0.007097 DEGREES
                   ***
01C6   B6 12               LDA    LOBIN        IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
01C8   A4 1F               AND    #%00011111   ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
01CA   26 0F               BNE    NO_32
01CC   B6 11               LDA    MIDBIN       IF THE LOW SIX BITS OF 'MIDBIN' ARE ZERO
01CE   27 07               BEQ    MODLO        AND 'HIBIN' .NE. ZERO
01D0   A4 3F               AND    #%00111111   THEN THE NUMBER IS MODULO 16,384, AND WE
01D2   26 03               BNE    MODLO        DON'T WANT TO SET 'MOD_32,STAT', UNLESS
01D4   0D 11 04            BRCLR  B6,MIDBIN,NO_32  THE NUMBER IS ALSO MODULO 32,768.
                   ***
01D7   1C 25       MODLO   BSET   MOD_32,STAT
01D9   20 02               BRA    DECBIN
                   ***
01DB   1D 25       NO_32   BCLR   MOD_32,STAT
                   ***
                   ***
                   ***************  DECREMENT THE BINARY COUNTER (BINCT).  ****************
                   ***
01DD   B6 12       DECBIN  LDA    LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
01DF   A0 01               SUB    #1      LOBIN = LOBIN - 1 ; BORROW -> C,CCR
01E1   B7 12               STA    LOBIN
                   ***
01E3   B6 11               LDA    MIDBIN
01E5   A2 00               SBC    #0      SUBTRACT THE CARRY FROM THE MIDDLE BYTE.
01E7   B7 11               STA    MIDBIN
                   ***
01E9   B6 10               LDA    HIBIN
01EB   A2 00               SBC    #0      SUBTRACT THE CARRY FROM THE HIGH BYTE.
01ED   B7 10               STA    HIBIN
                   ***
01EF   B6 10               LDA    HIBIN
01F1   2A 29               BPL    CCWPOS       IF HIBIN .GE. 0 , WE'RE ROTATING CCW TOWARD
                   ***                         THE ORIGIN.
01F3   A6 FF               LDA    #-1     --
01F5   B1 10               CMP    HIBIN    --
01F7   26 1C               BNE    CCWNEG     --  ELSE IF BINCT .NE. -1 ,
01F9   B1 11               CMP    MIDBIN      -- WE'RE ROTATING CCW AWAY
01FB   26 18               BNE    CCWNEG     --  FROM THE ORIGIN.
```

```
01FD   B1 12                 CMP     LOBIN    --
01FF   26 14                 BNE     CCWNEG  --
                     ***
0201   14 25                 BSET    NEGTIV,STAT   ELSE, WE'VE GONE THROUGH ORIGIN IN CCW
                     ***                           DIRECTION.  SET NEGATIVE SIGN.
                     ***                           AND SET ALL COUNTERS APPROPRIATELY.
0203   A6 03                 LDA     #03      --
0205   B7 13                 STA     PTR4      --
0207   B7 1A                 STA     HUNDEG      -- DEGRES = 360.00
0209   A6 3C                 LDA     #60       --
020B   B7 14                 STA     PTR3     --
020D   AE 15                 LDX     #PTR2    --
020F   7F            CLREM   CLR     ,X          --
0210   5C                    INCX                -- EVERYTHING ELSE IS ZERO BEFORE CHANGE.
0211   A3 19                 CPX     #CTPTR1   --
0213   23 FA                 BLS     CLREM    --
                     ***
0215   AD 16         CCWNEG  BSR     ADDBCD
0217   CD 02 FD              JSR     DECPOS
021A   20 06                 BRA     UPOUT
                     ***
021C   CD 02 CA      CCWPOS  JSR     SUBBCD
021F   CD 02 FD              JSR     DECPOS
                     ***
                     ***
                     **
                     ******************************************************************************
                     **
                     ** OUTPUT ROUTINE. ROUTINE TO PRINT DATA TO THE OUTPUT PORTS.  BY
                     **       CALLING THE APPROPRIATE SUBROUTINE.('OUTCT' TO OUTPUT THE
                     **       THE COUNT AND 'OUTPOS' TO OUTPUT THE POSITION).
                     **
       0222          UPOUT  EQU     $
                     **
0222   09 25 04              BRCLR   POSCT,STAT,PUTCT
                     **
0225   CD 03 68              JSR     OUTPOS
0228   80                    RTI
                     **
0229   CD 03 4E      PUTCT   JSR     OUTCT
022C   80                    RTI
                     **
                     ******************************************************************************
                     ***********  SUBROUTINE TO INCREMENT THE BCD COUNTER (BCDCT).  *********
                     ***
022D   B6 19         ADDBCD  LDA     CTPTR1
022F   AB 01                 ADD     #1
0231   A1 63                 CMP     #99      CTPTR > 99 ?
0233   23 05                 BLS     OK1      NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
0235   A0 64                 SUB     #100     YES... MODIFY THE CTPTR,
0237   99                    SEC              SET THE CARRY, AND
0238   20 01                 BRA     OK1A     USE TABLE LOOK UP.
                     ***
023A   98            OK1     CLC                       NO CARRY EXISTS IF WE ENTER AT THIS POINT.
023B   B7 19         OK1A    STA     CTPTR1  --
023D   97                    TAX                --
                     ***                       -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
023E   D6 03 BE              LDA     TABLE,X   --
0241   B7 20                 STA     TENONE  --
0243   24 24                 BCC     NOMO             AND CONTINUE ONLY IF THERE WAS A CARRY.
                     ***
                     ***
0245   B6 18                 LDA     CTPTR2
0247   A9 00                 ADC     #0       ADD THE CARRY.
0249   A1 63                 CMP     #99      CTPTR > 99 ?
024B   23 05                 BLS     OK2      NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
```

```
024D  A0 64              SUB    #100     YES... MODIFY THE CTPTR,
024F  99                 SEC             SET THE CARRY, AND
0250  20 01              BRA    OK2A     USE TABLE LOOK UP.
                  ***
0252  98          OK2    CLC                    NO CARRY EXISTS IF WE ENTER AT THIS POINT.
0253  B7 18       OK2A   STA    CTPTR2  --
0255  97                 TAX              --
                  ***                      -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0256  D6 03 BE           LDA    TABLE,X  --
0259  B7 1F              STA    HUNDRD  --
025B  24 0C              BCC    NOMO            AND CONTINUE ONLY IF THERE WAS A CARRY.
                  ***
025D  B6 17              LDA    CTPTR3
025F  A9 00              ADC    #0              ADD THE CARRY.
0261  B7 17              STA    CTPTR3  --
0263  97                 TAX               --
                  ***                       -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0264  D6 03 BE           LDA    TABLE,X  --
0267  B7 1E              STA    TENTHO  --
                  ***
0269  81          NOMO   RTS
                  ***
                  ****************************************************************************
                  *******  SUBROUTINE TO INCREMENT THE POSITION COUNTER (DEGRES).  *******
                  ***
                  ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                  ****     NUMBER.
                  ****
026A  0D 25 04    INCPOS BRCLR  MOD_32,STAT,INC7   'MOD_32,STAT' SET ?
                  ****
026D  A6 08              LDA    #8                     YES ...
026F  20 02              BRA    INC             INCREMENT THE POSITION BY 0.008 DEGREES.
                  ****
0271  A6 07       INC7   LDA    #7                     NO ....
0273  B7 22       INC    STA    POSINC          INCREMENT THE POSITION BY 0.007 DEGREES.
                  ****
                  **** ROUTINE TO INCREMENT THE POSITION COUNTER ,'DEGREES',BY A
                  ****     PREDETERMINED AMOUNT, 'POSINC'.
                  ****
0275  B6 16              LDA    PTR1
0277  BB 22              ADD    POSINC
0279  A1 09              CMP    #9       PTR1 > 9 ?
027B  23 05              BLS    OK3      NO, WE'RE OK HERE.  LOOK UP THE FIRST DIGIT.
027D  A0 0A              SUB    #10      YES... MODIFY THE CTPTR,
027F  99                 SEC             SET THE CARRY, AND
0280  20 01              BRA    OK3A     USE TABLE LOOK UP.
                  ****
0282  98          OK3    CLC                    NO CARRY EXISTS IF WE ENTER AT THIS POINT.
0283  B7 16       OK3A   STA    PTR1    --
0285  97                 TAX              --
                  ****                     -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
0286  D6 03 BE           LDA    TABLE,X  --
0289  B7 1D              STA    THOUTH  --
028B  24 3C              BCC    DONE             AND CONTINUE ONLY IF THERE WAS A CARRY.
                  ****
                  ****
028D  B6 15              LDA    PTR2
028F  A9 00              ADC    #0       ADD THE CARRY.
0291  A1 63              CMP    #99      PTR2 > 99 ?
0293  23 05              BLS    OK4      NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
0295  A0 64              SUB    #100     YES...MODIFY THE CTPTR,
0297  99                 SEC             SET THE CARRY,
0298  20 01              BRA    OK4A     AND USE TABLE LOOK UP.
                  ****
029A  98          OK4    CLC                    NO CARRY EXISTS IF WE ENTER AT THIS POINT.
029B  B7 15       OK4A   STA    PTR2    --
```

```
029D   97                    TAX                   --
                     ****                             -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
029E   D6 03 BE              LDA    TABLE,X   --
02A1   B7 1C                 STA    HUNDTH  --
02A3   24 24                 BCC    DONE            AND CONTINUE ONLY IF THERE WAS A CARRY.
                     ****
                     ****
02A5   B6 14                 LDA    PTR3
02A7   A9 00                 ADC    #0      ADD THE CARRY.
02A9   A1 63                 CMP    #99     PTR3 > 99 ?
02AB   23 05                 BLS    OK5     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
02AD   A0 64                 SUB    #100    YES... MODIFY THE CTPTR,
02AF   99                    SEC            SET THE CARRY, AND
02B0   20 01                 BRA    OK5A    USE TABLE LOOK UP.
                     ****
02B2   98            OK5     CLC                        NO CARRY EXISTS IF WE ENTER AT THIS POINT.
02B3   B7 14         OK5A    STA    PTR3    --
02B5   97                    TAX              --
                     ****                           -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02B6   D6 03 BE              LDA    TABLE,X   --
02B9   B7 1B                 STA    ONEDEG  --
02BB   24 0C                 BCC    DONE            AND CONTINUE ONLY IF THERE WAS A CARRY.
                     ****
02BD   B6 13                 LDA    PTR4
02BF   A9 00                 ADC    #0      ADD THE CARRY.
02C1   B7 13                 STA    PTR4    --
02C3   97                    TAX              --
                     ****                             -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02C4   D6 03 BE              LDA    TABLE,X   --
02C7   B7 1A                 STA    HUNDEG  --
                     ****
02C9   81            DONE    RTS
                     ***
                     **
                     ***************************************************************************
                     ********  SUBROUTINE TO DECREMENT THE BCD COUNTER (BCDCT).  ************
                     ***
02CA   B6 19         SUBBCD  LDA    CTPTR1
02CC   A0 01                 SUB    #1      CTPTR > 99 ?
02CE   24 03                 BCC    OK6     NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
02D0   AB 64                 ADD    #100    YES, MODIFY THE CTPTR, AND
02D2   99                    SEC            GENERATE A BORROW.
                     ***
02D3   B7 19         OK6     STA    CTPTR1  --
02D5   97                    TAX              --
                     ***                            -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
02D6   D6 03 BE              LDA    TABLE,X   --
02D9   B7 20                 STA    TENONE  --
02DB   24 1F                 BCC    COMPLT        AND CONTINUE ONLY IF THERE WAS A BORROW.
                     ***
                     ***
02DD   B6 18                 LDA    CTPTR2
02DF   A2 00                 SBC    #0      SUBTRACT THE CARRY. CTPTR > 99 ?
02E1   24 03                 BCC    OK7     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
02E3   AB 64                 ADD    #100    YES, MODIFY THE CTPTR, AND
02E5   99                    SEC            GENERATE A BORROW.
                     ***
02E6   B7 18         OK7     STA    CTPTR2  --
02E8   97                    TAX              --
                     ***                              -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02E9   D6 03 BE              LDA    TABLE,X   --
02EC   B7 1F                 STA    HUNDRD  --
02EE   24 0C                 BCC    COMPLT          AND CONTINUE ONLY IF THERE WAS A CARRY.
                     ***
02F0   B6 17                 LDA    CTPTR3
02F2   A2 00                 SBC    #0      SUBTRACT THE BORROW.
```

```
02F4   B7 17              STA    CTPTR3  --
02F6   97                 TAX              --
                   ***                      -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02F7   D6 03 BE           LDA    TABLE,X  --
02FA   B7 1E              STA    TENTHO  --
                   ***
02FC   81          COMPLT RTS
                   ***
                   ***************************************************************************
                   *******  SUBROUTINE TO DECREMENT THE POSITION COUNTER (DEGRES).  *******
                   ***
                   ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                   ****     NUMBER.
                   ****
02FD   00 25 04    DECPOS BRCLR  MOD_32,STAT,DEC7        'MOD_32,STAT' SET ?
                   ****
0300   A6 08              LDA    #8                      YES...
0302   20 02              BRA    DEC           DECREMENT THE POSITION BY 0.008 DEGREES.
                   ****
0304   A6 07       DEC7   LDA    #7                      NO ....
0306   B7 22       DEC    STA    POSINC        DECREMENT THE POSITION BY 0.007 DEGREES.
                   ****
                   **** ROUTINE TO DECREMENT THE POSITION COUNTER ,'DEGREES',BY A
                   ****     PREDETERMINED AMOUNT, 'POSINC'.
                   ****
0308   B6 16              LDA    PTR1
030A   B0 22              SUB    POSINC  PTR1 < 0 ?
030C   24 03              BCC    OK8     NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.
030E   AB 0A              ADD    #10     YES, MODIFY THE CTPTR, AND
0310   99                 SEC            GENERATE A BORROW.
                   ****
0311   B7 16       OK8    STA    PTR1    --
0313   97                 TAX              --
                   ****                    -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
0314   D6 03 BE           LDA    TABLE,X  --
0317   B7 1D              STA    THOUTH  --
0319   24 32              BCC    DUNSUB       AND CONTINUE ONLY IF THERE WAS A BORROW.
                   ***
                   ***
031B   B6 15              LDA    PTR2
031D   A2 00              SBC    #0      SUBTRACT THE BORROW.  PTR2 < 0 ?
031F   24 03              BCC    OK9     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
0321   AB 64              ADD    #100    YES, MODIFY THE CTPTR, AND
0323   99                 SEC            GENERATE A BORROW.
                   ***
0324   B7 15       OK9    STA    PTR2    --
0326   97                 TAX              --
                   ***                     -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0327   D6 03 BE           LDA    TABLE,X  --
032A   B7 1C              STA    HUNDTH  --
032C   24 1F              BCC    DUNSUB        AND CONTINUE ONLY IF THERE WAS A CARRY.
                   ***
                   ***
032E   B6 14              LDA    PTR3
0330   A2 00              SBC    #0      SUBTRACT THE BORROW.  PTR3 < 0 ?
0332   24 03              BCC    OK10    NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
0334   AB 64              ADD    #100    YES, MODIFY THE CTPTR, AND
0336   99                 SEC            GENERATE A BORROW.
                   ****
0337   B7 14       OK10   STA    PTR3    --
0339   97                 TAX              --
                   ****                     -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
033A   D6 03 BE           LDA    TABLE,X  --
033D   B7 1B              STA    ONEDEG  --
033F   24 0C              BCC    DUNSUB        AND CONTINUE ONLY IF THERE WAS A CARRY.
                   ****
```

```
0341   B6 13                LDA    PTR4
0343   A2 00                SBC    #0      SUBTRACT THE BORROW.
0345   B7 13                STA    PTR4    --
0347   97                   TAX              --
                     ****                      -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0348   D6 03 BE             LDA    TABLE,X   --
034B   B7 1A                STA    HUNDEG  --
                     ****
034D   81            DUNSUB RTS
                     ***
                     **
                     **
                     ****************************************************************************
                     **
                     ** OUTPUT COUNT (OUTCT).  SUBROUTINE TO MOVE THE CURRENT COUNT (BCDCT)
                     **       TO THE OUTPUT PORTS.  REMOVES THE DECIMAL POINT FROM THE
                     **       DISPLAY AND BLANKS ALL BUT THE LEAST SIGNIFICANT DIGIT. ALSO
                     **       SETS THE MINUS SIGN IF APPROPRIATE.
                     **
       034E          OUTCT  EQU    $
                     **
034E   B6 20                LDA    TENONE
0350   B7 02                STA    PORTC
                     **
0352   B6 1F                LDA    HUNDRD
0354   B7 00                STA    PORTA
                     **
0356   B6 1E                LDA    TENTHO
0358   B7 01                STA    PORTB
                     **
035A   1E 01                BSET   DECPT,PORTB
035C   19 01                BCLR   BLANK,PORTB
                     **
035E   04 25 04             BRSET  NEGTIV,STAT,MINUS
0361   1C 01                BSET   POSTIV,PORTB
0363   20 02                BRA    ALLDUN
                     **
0365   1D 01         MINUS  BCLR   POSTIV,PORTB
                     **
0367   81            ALLDUN RTS
                     **
                     **
                     ** OUTPUT POSITION (OUTPOS).  SUBROUTINE TO MOVE THE CURRENT POSITION
                     **       COUNT (BCDCT) TO THE OUTPUT PORTS.  THE DECIMAL POINT IS
                     **       DISPLAYED , AND ONLY THE MOST SIGNIFICANT DIGIT IS BLANKED.
                     **
       0368          OUTPOS EQU    $
                     **
0368   B6 1D                LDA    THOUTH  --
036A   A1 05                CMP    #5        --
036C   25 38                BLO    TRUNC      --    IF 5 > 'THOUTH' SIMPLY TRUNCATE THE
036E   B6 1C                LDA    HUNDTH        -- DISPLAY.  OTHERWISE...
0370   A4 09                AND    #9            -- IF THE LAST DIGIT ISN'T A NINE IT IS
0372   A1 09                CMP    #9            -- EASY TO ROUND UP.  JUST ADD A ONE.
0374   26 28                BNE    DECIMAL       --
0376   B6 1C                LDA    HUNDTH        -- BUT IF THE LAST DIGIT IS A NINE CHECK TO
0378   A1 99                CMP    #$99          -- SEE IF IT'S 99.  IF SO IT GETS GRIM.
037A   27 04                BEQ    UGLY          --
037C   AB 07                ADD    #7            -- IF THE NUMBER IS X9 AND X .NE. 9, THEN
037E   20 28                BRA    PCOUT         -- JUST ADD SEVEN TO ROUND UP. DUE TO
                     **                          -- HEXIDECIMAL.
                     **                          -- IF THE LOW TWO DIGITS ARE BOTH NINES
0380   A6 00         UGLY   LDA    #00        --    AND WE NEED TO ROUND UP....
0382   B7 02                STA    PORTC    --      MAKE THE LOW TWO DIGITS BOTH ZEROS
0384   99                   SEC           --        AND SET THE CARRY.
                     **
```

```
0385    B6 1B                     LDA     ONEDEG  --       CHECK THE LAST DIGIT AS BEFORE.
0387    A4 09                     AND     #9        --     IF USING THIS PORTION OF THE CODE
0389    A1 09                     CMP     #9          --   THERE HAD TO BE A CARRY.
038B    26 1E                     BNE     NEXT          -- IF THE LAST DIGIT IS NOT A NINE USE THE
038D    B6 1B                     LDA     ONEDEG        -- ADC INSTRUCTION BELOW.
038F    A1 99                     CMP     #$99          -- IF IT IS A NINE, IS THE NEXT ONE A NINE
0391    27 04                     BEQ     RLUGLY        -- ALSO?
0393    AB 07                     ADD     #7        --     IF NOT JUST ADD SEVEN,
0395    20 18                     BRA     PAOUT   --       AND DISPLAY THE OUTPUT.
                        **
0397    A6 00           RLUGLY    LDA     #00     --
0399    B7 00                     STA     PORTA     --     IF SO ROUND UP THE MOST SIGNIFICANT
039B    99                        SEC               --     DIGIT AND SET EVERYTHING ELSE TO ZERO.
039C    20 13                     BRA     NEXT1   --
                        **
039E    B6 1C           DECIMAL   LDA     HUNDTH --
03A0    AB 01                     ADD     #1        --
                        **                             -- THIS IS ALL THAT NEEDS TO BE DONE IF
03A2    B7 02                     STA     PORTC     --     THE LAST DIGIT IS NOT A NINE.
03A4    20 05                     BRA     NEXT    --
                        **
03A6    B6 1C           TRUNC     LDA     HUNDTH  --
03A8    B7 02           PCOUT     STA     PORTC     --  AND IF THERE IS NO CARRY IT'S EVEN EASIER.
03AA    98                        CLC             --
                        **
03AB    B6 1B           NEXT      LDA     ONEDEG
03AD    A9 00                     ADC     #0
03AF    B7 00           PAOUT     STA     PORTA
                        **
03B1    B6 1A           NEXT1     LDA     HUNDEG
03B3    A9 00                     ADC     #0
03B5    B7 01                     STA     PORTB
                        **
03B7    1C 01                     BSET    POSTIV,PORTB
03B9    18 01                     BSET    BLANK,PORTB
03BB    1F 01                     BCLR    DECPT,PORTB
                        **
03BD    81                        RTS
                        **
                        **
                        ******************************************************************************
                        **
                        ** SET UP THE TABLE TO BE USED WITH BCD INCREMENT/DECREMENT ROUTINES.
                        **
                        *         ENDS
                        *         DATA
03BE    00 01 02 03 04  TABLE     FCB     $00,$01,$02,$03,$04,$05,$06,$07,$08,$09
03C3    05 06 07 08 09
03C8    10 11 12 13 14            FCB     $10,$11,$12,$13,$14,$15,$16,$17,$18,$19
03CD    15 16 17 18 19
03D2    20 21 22 23 24            FCB     $20,$21,$22,$23,$24,$25,$26,$27,$28,$29
03D7    25 26 27 28 29
03DC    30 31 32 33 34            FCB     $30,$31,$32,$33,$34,$35,$36,$37,$38,$39
03E1    35 36 37 38 39
03E6    40 41 42 43 44            FCB     $40,$41,$42,$43,$44,$45,$46,$47,$48,$49
03EB    45 46 47 48 49
03F0    50 51 52 53 54            FCB     $50,$51,$52,$53,$54,$55,$56,$57,$58,$59
03F5    55 56 57 58 59
03FA    60 61 62 63 64            FCB     $60,$61,$62,$63,$64,$65,$66,$67,$68,$69
03FF    65 66 67 68 69
0404    70 71 72 73 74            FCB     $70,$71,$72,$73,$74,$75,$76,$77,$78,$79
0409    75 76 77 78 79
040E    80 81 82 83 84            FCB     $80,$81,$82,$83,$84,$85,$86,$87,$88,$89
0413    85 86 87 88 89
0418    90 91 92 93 94            FCB     $90,$91,$92,$93,$94,$95,$96,$97,$98,$99
041D    95 96 97 98 99
```

```
                        *       ENDS
                        *       CODE
                        *****************************************************************************
                        **
                        **                          SET UP MASK OPTION REGISTER.
                        **
0422                            ABSOLUTE
                        **
                        **
0F38                            ORG     MOR
0F38    07                      FCB     #BIT2+BIT1+BIT0
                        **
                        **      COMMENTS:
                        **      BIT 7   CLOCK SOURCE  0 = CRYSTAL.
                        **      BIT 6   TIMER OPTION  0 = INTERNAL.
                        **      BIT 5   TIMER/CLOCK SOURCE  0 = INTERNAL.
                        **      BIT 4   NOT USED.
                        **      BIT 3   NOT USED.
                        **      BIT 2   SET  -
                        **      BIT 1   SET    -  PRESCALE SELECT  111 => 128
                        **      BIT 0   SET  -
                        **
                        **
                        *****************************************************************************
                        **
                        **                          ASSIGN INTERRUPT VECTORS.
                        **
0FF8                            ORG     INTRPT
                        **
0FF8    012E                    FDB     BLINK   TIMER/INT2 INTERRUPT VECTOR.
0FFA    014D                    FDB     COUNT   EXTERNAL INTERRUPT VECTOR.
0FFC    014D                    FDB     COUNT   SOFTWARE INTERRUPT VECTOR, NOT USED.
0FFE    0080                    FDB     RESTRT  RESET VECTOR.
                        **
                        **
                        **
                                ENDS
1000                            END
```

Lines Assembled : 1079   Assembly Errors : 0

C. TILT

```
                              TTL                  POSITION DETERMINING PROGRAM (ELEVATION)
                       *                 LATEST REVISION          9 MAY 89
                       *                 FILE NAME                TILT.ASM
                       **
                       ** PROGRAM DESCRIPTION
                       **
                       **
                       **
                       ** I/O REGISTER ADDRESSES
                       **
        0000           PORTA   EQU     $0000   I/O PORT A
        0001           PORTB   EQU     $0001   I/O PORT B
        0002           PORTC   EQU     $0002   I/O PORT C
        0003           PORTD   EQU     $0003   INPUT PORT D
                       **
                       ** DATA DIRECTION REGISTER OFFSET
                       **
        0004           DDR     EQU     4       (eg. DDR FOR PORT A IS  PORTA+DDR )
                       **
                       ** OTHERS
                       **
        0008           TIMER   EQU     $0008   EIGHT BIT TIMER REGISTER.
        0009           TCR     EQU     $0009   TIMER CONTROL REGISTER.
        000A           MR      EQU     $000A   MISCELLANEOUS REGISTER.
        0010           RAM     EQU     $0010   START OF ON-CHIP RAM(112 - 31 FOR STACK)
        0080           ZROM    EQU     $0080   PAGE ZERO OF ROM.
        0100           ROM     EQU     $0100   START OF MAIN ROM.
        0F38           MOR     EQU     $0F38   MASK OPTION REGISTER.
        0FF8           INTRPT  EQU     $0FF8   LOCATION OF INTERRUPT VECTORS.
        1000           MEMSIZ  EQU     $1000   MEMORY ADDRESS SIZE.
                       **
                       ** EQUATES
                       **
        0001           BIT0    EQU     1
        0002           BIT1    EQU     2
        0004           BIT2    EQU     4
        0008           BIT3    EQU     8
        0010           BIT4    EQU     16
        0020           BIT5    EQU     32
        0040           BIT6    EQU     64
        0080           BIT7    EQU     128
                       **
        0000           B0      EQU     0
        0001           B1      EQU     1
        0002           B2      EQU     2
        0003           B3      EQU     3
        0004           B4      EQU     4
        0005           B5      EQU     5
        0006           B6      EQU     6
        0007           B7      EQU     7
                       **
                       ** EQUATES FOR THE TIMER CONTROL REGISTER
                       **
                       ***
        0007           TIR     EQU     7       TIMER INTERRUPT REQUEST. 1 = REQUEST, 0 = NO REQ.
        0006           TIM     EQU     6       TIMER INTERRUPT MASK. 1 = DISABLED, 0 = ENABLED.
        0005           TIN     EQU     5       EXTERNAL OR INTERNAL CLOCK SOURCE. 1 = EXT, 0 = INT.
        0004           TEE     EQU     4       EXTERNAL CLOCK ENABLE. NOT USED.
        0003           PSC     EQU     3       PRESCALER CLEAR. NOT USED.
        0002           PS2     EQU     2       (PS2)  --
        0001           PS1     EQU     1       (PS1)     |--  PRESCALER SELECT BITS.
```

```
0000             PSO     EQU     0       (PSO)  --
                 **
                 ** EQUATES FOR THE STATUS BYTE, 'STAT'.
                 ***
                 ***
                 **
0007             UD      EQU     7       COUNT DIRECTION?  1 = UP, 0 = DOWN.
0006             MOD_32  EQU     6       IS 'BINCT' MODULO 32?   1 = YES, 0 = NO.
0005             FLASH   EQU     5       BLINK THE DISPLAY?  1 = YES, 0 = NO.
0004             POSCT   EQU     4       DISPLAY POSITION OR COUNT?  1 = POS, 0 = COUNT.
0003             L_SET   EQU     3       VALUE OF 'MODE,PORTD' LAST TIME.
0002             NEGTIV  EQU     2       IS 'BCDCT'NEGATIVE NUMBER?  1 = YES, 0 = NO.
                 ***             1       NOT USED.
                 ***             0       NOT USED.
                 ***
                 ***
                 ** I/O EQUATES AND DESCRIPTIONS.
                 ***
                 ***
                 ***      PORT A  (I/O)
                 ***
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***      |          BCD DIGIT #4         |          BCD DIGIT #3         |
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***      |  D4   |  C4   |  B4   |  A4   |  D3   |  C3   |  B3   |  A3   |
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 *** BIT      7       6       5       4       3       2       1       0
                 ***
                 ***
                 ***      PORT B  (I/O)
                 ***
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***      |        DISPLAY CONTROL        |           NOT USED            |
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***      | DECPT | POSTIV|       | BLANK |       |       |       |       |
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 *** BIT      7       6       5       4       3       2       1       0
                 ***
0007             DECPT   EQU     7       TO DISPLAY THE DECIMAL POINT...DECPT IS CLEARED
0006             POSTIV  EQU     6       USED TO DISPLAY NEGATIVE SIGN...CLEARED TO SHOW
                 ***                     MINUS SIGN.
0004             BLANK   EQU     4       TO BLANK DIGITS 2 AND 3...CLEAR BLANK.
                 ***                     DIGITS 4 AND 5 ARE ALWAYS BLANKED.
                 ***                     DIGIT 1 IS NEVER BLANKED.
                 ***
                 ***      PORT C  (I/O)
                 ***
                 ***      +-------+-------+-------+-------+-------+-------+-------+-------+
                 ***      |          BCD DIGIT #2         |BCD DIGIT #1(LEAST SIGNIFICANT)|
                 ***      +-------+-------+-------+-------+-------+-------+-------+------- +
                 ***      |  D2   |  C2   |  B2   |  A2   |  D1   |  C1   |  B1   |  A1   |
                 ***      +-------+-------+-------+-------+-------+-------+-------+------- +
                 *** BIT      7       6       5       4       3       2       1       0
                 ***
                 ***
                 ***      PORT D  (INPUT ONLY)
                 ***
                 ***      +-------+-------+-------+-------+-------+-------+-------+------- +
                 ***      | CH_A  |  INT2 | CH_B  | FUNCT |  SET  |       |       |       |
                 ***      +-------+-------+-------+-------+-------+-------+-------+------- +
                 *** BIT      7       6       5       4       3       2       1       0
                 ***
0007             CH_A    EQU     7       INDICATES THE STATUS OF CHANNEL A.
0006             INT2    EQU     6       INTERRUPT #2.  USED TO CHANGE DISPLAY MODES.
0005             CH_B    EQU     5       INDICATES THE STATUS OF CHANNEL B.
0004             FUNCT   EQU     4       USED TO PUT THE PROGRAM IN A MODE THAT WILL ALLOW
```

```
                             ***                      'HYST' TO BE INCREMENTED.
          0003               SET     EQU    3         INCREMENTS 'HYST' WHEN TOGGLED AND FUNCT IS LOW.
                             ***
                             ***
                             ***********************************************************************
                             **                                                                    *
                             **                          RAM VARIABLES                             *
                             **                                                                    *
                             ***********************************************************************
                             **
                             ** RESERVE MEMORY SPACE FOR THE PROGRAM VARIABLES.
                             **
    0000                             DATA
                             **
                             **
    0000                             ABSOLUTE (ABSOLUTE ADDRESSING USED HERE TO RELATIVE DIRECTIVE)
                             **
    0010                             ORG     RAM        START OF RAM.
                             **
                             *** BINARY COUNT.
    0010                     BINCT   RMB    2
          0010               HIBIN   EQU    BINCT       HI BYTE.
          0011               LOBIN   EQU    BINCT+1     LO BYTE.
                             **
                             *** POSITION POINTERS.
    0012                     PTR     RMB    3           EACH BYTE POINTS TO A POSITION IN THE
                             **                         TABLE THAT CONTAINS ONE OR TWO DIGITS
                             **                         OF THE BCD POSITION.
          0012               PTR3    EQU      PTR       MOST SIGNIFICANT DIGITS.
          0013               PTR2    EQU      PTR+1
          0014               PTR1    EQU      PTR+2     LEAST SIGNIFICANT DIGIT.
                             **
                             *** COUNT POINTERS.
    0015                     CTPTR   RMB    2           EACH BYTE POINTS TO A POSITION IN THE
                             **                         TABLE THAT CONTAINS TWO OF THE DIGITS
                             **                         IN THE BCD COUNT.
          0015               CTPTR2  EQU    CTPTR       MOST SIGNIFICANT DIGITS.
          0016               CTPTR1  EQU    CTPTR+1     LEAST SIGNIFICANT DIGITS.
                             **
                             *** BCD POSITION IN DEGREES.
    0017                     DEGRES  RMB    3
          0017               ONEDEG  EQU    DEGRES            CONTENTS X   1.000
          0018               HUNDTH  EQU    DEGRES+1          CONTENTS X   0.010
          0019               THOUTH  EQU    DEGRES+2        + CONTENTS X   0.001
                             ***                            --------------------
                             ***                              POSITION IN DEGREES
                             **
                             *** BCD COUNT.
    001A                     BCDCT   RMB    2
          001A               HUNDRD  EQU    BCDCT             CONTENTS X    100
          001B               TENONE  EQU    BCDCT+1         + CONTENTS X      1
                             ***                          -----------------------
                             ***                          NUMBER OF PULSES COUNTED
                             ***
                             *** HYSTERESIS COUNTER. POINTS TO A NUMBER IN THE TABLE THAT IS THE
                             ***      AMOUNT OF HYSTERESIS PRESENT IN THE SYSTEM.  INITIALIZED TO 6.
    001C                     HYSTPT  RMB      1
                             **
                             *** POSITION INCREMENT.  CONTAINS A NUMBER, THAT WHEN MULTIPLIED BY 0.001
                             ***      IS THE NUMBER OF DEGREES THAT THE POSITION COUNTER (BCDPOS) IS
                             ***      TO BE INCREMENTED OR DECREMENTED DURING PROGRAM EXECUTION.
                             ***      THE VALUE OF 'POSINC', DETERMINED EXPERIMENTALLY, SHOULD BE
                             ***      7.0452.  SINCE THE PROGRAM IS DESIGNED WORK WITH INTEGERS ONLY
                             ***      THIS NUMBER IS ROUNDED TO 7.  TO REDUCE THE CUMULATIVE EFFECT OF
                             ***      THE ROUND OFF, EVERY 32 COUNTS 'POSINC' IS SET EQUAL TO 8.  THIS
                             ***      AGAIN LEADS TO SOME CUMULATIVE ERROR, BUT THE SMALL ANGULAR RANGE
```

```
                      ***     OF THE TILT ANGLE (10.5 DEGREES) ALLOWS US TO NEGLECT ANY FURTHER
                      ***     MODIFICATIONS.
                      ***
0010                  POSINC  RMB     1
                      ***
                      *** HYSTERESIS VARIABLES.  USED TO ELIMINATE THE EFFECTS OF BACKLASH ON
                      ***     THE POSITION MEASUREMENTS.
                      ***
001E                  HYST    RMB     1       THE THRESHHOLD VALUE DETERMINED
                      ***                     EXPERIMENTALLY.
001F                  HYSTCT  RMB     1       CURRENT AMOUNT OF HYSTERESIS MEASURED.
                      ***
                      *** STATUS BYTE.  USED TO KEEP TRACK OF WHAT IS GOING ON.
                      ***
0020                  STAT    RMB     1       CURRENT STATUS.
0021                  LSTAT   RMB     1       PREVIOUS/LAST STATUS.  USED TO KEEP TRACK OF
                      ***                     L_SET ONLY.
                      ***
                      *** TIMER COUNTER.  USED IN CONJUNCTION WITH THE TIMER PRESCALER AND THE
                      ***     TDR TO KEEP TRACK OF ONE SEC. INTERVALS.  USED IN BLINKING THE
                      ***     DISPLAY.  INITIALLY SET TO 31, WHEN THE 'FLASH' BIT OF 'STAT'
                      ***     IS SET.  TIMCT IS DECREMENTED EACH CLOCK INTERRUPT (APPROX. 31
                      ***     TIMES PER SEC).  RESET TO 31 WHEN CONTENTS GO TO ZERO.
                      ***     WHEN (TIMCT)=0 THE DISPLAY WILL TOGGLE.
                      ***
0022                  TIMCT   RMB     1
                      **
                              ENDS
                      **
                      ***
                      ******************************************************************************
                      **                                                                           *
                      **                          PAGE ZERO ROM
                      **                                                                           *
                      ******************************************************************************
                      **
                      **                       INITIALIZATION ROUTINE.
                      **
                      **
0000                          CODE
                      **
0080                          ORG     ZROM    PAGE ZERO ROM.
                      **
0080                          RELATIVE        RELATIVE ADDRESSING MUST BE USED FOR THE BRANCH.
                      **
        0080          RESTRT  EQU     $       THIS IS THE ENTRY POINT WHEN AN EXTERNAL
                      ***                     INTTERRUPT OCCURS.
                      **
                      ******************************************************************************
                      **
                      ***              INITIALIZE THE PC AND CLEAR RAM.
                      ***
                      ***
0080    9B                    SEI             SET INTERUPT TO AVOID INTERUPTION AND
0081    9C                    RSP             RESET THE STACK POINTER. JUST IN CASE!
                      ***
0082    AE 10                 LDX     #BINCT  CLEAR ALL OF THE VARIABLES BETWEEN
0084    7F            CLRIT   CLR     ,X      'BINCT' AND 'TIMCT' (INCLUSIVE).NOTE
0085    5C                    INCX            THAT THIS SETS THE COUNTER AND THE POS-
0086    A3 22                 CPX     #TIMCT  ITION TO ZERO. THIS MEANS THAT ROTATION
0088    23 FA                 BLS     CLRIT   SHOULD START IN AN INCREASING (CW)
                      ***                     DIRECTION FROM THE MOST CCW POSITION
                      ***                     AFTER A RESET.
                      ***
008A                          ABSOLUTE        BACK TO ABSOLUTE ADDRESSING.
                      ***
```

```
                    ************************************************************************
                    ***
                    ***                       ESTABLISH I/O PORTS.
                    ***
008A  A6 FF               LDA    #-1          PORTS A,B,C ARE CONFIGURED AS
008C  B7 04               STA    PORTA+DDR    ALL OUTPUT. PORT D IS ALL INPUT
008E  B7 05               STA    PORTB+DDR    SO THERE IS NO MASK TO SET.
0090  B7 06               STA    PORTC+DDR
                    ***
                    ************************************************************************
                    ***                 SET UP THE STATUS REGISTER.
                    ***
0092  A6 08               LDA    #%00001000   --
0094  B4 03               AND    PORTD          |--> SET UP 'L_SET' BIT OF 'STAT'.
0096  B7 20               STA    STAT         --
                    ***
0098  1C 20               BSET   MOD_32,STAT  0 IS MODULO 32.
                    **
                    ************************************************************************
                    ***
                    ***                  INITIALIZE HYSTCT.
                    ***
009A  A6 06               LDA    #06
009C  B7 1E               STA    HYST
009E  B7 1C               STA    HYSTPT
                    ***
                    ************************************************************************
                    **
                    **      SET UP THE TIMER FOR A 4 MHZ CRYSTAL / 4 = 1 MHZ CLOCK.
                    ***
                    ***    NOTE:  THE MASK OPTION REGISTER IS IN ROM.  IT IS SET UP AT
                    ***           THE END OF THE PROGRAM.
                    ***                                  .
                    **********************  SET UP THE TCR.  **********************************
                    ***
00A0  A6 47               LDA       #BIT6+BIT2+BIT1+BIT0
                    ***             (TIM)|(PS2)(PS1)(PS0)
                    ***(DISABLE INTERRUPT)|(PRESCALE BY 128)
                    ***
00A2  B7 09               STA    TCR
                    ***
                    ***
                    *** SET UP THE TIMER.
                    ***
00A4  A6 FF               LDA    #255    1 MHZ/(128*255) = 30.6 (APPROX. 31)
00A6  B7 08               STA TIMER
                    ***
                    ****************  INITIALIZE THE TIMER COUNTER.  ***********************
                    ***
00A8  A6 1F               LDA    #31     PROVIDES FOR 1 SEC. BLINK INTERVAL.
00AA  B7 22               STA    TIMCT   FOR 2 SEC. INTERVAL JUST USE TIMECT=62, etc.
                    ***
                    ***
                    ***********************************************************************
                    **
                    **                   SET UP MISCELLANEOUS REGISTER.
                    **
00AC  1D 0A             BCLR    B6,MR    ENABLES THE SECOND INTERRUPT.
                    **
                    ************************************************************************
                    **
                    **                COUNT = 0 IS DISPLAYED INITIALLY.
                    **
00AE  CD 02 D8            JSR    OUTCT
00B1  1C 01               BSET   POSTIV,PORTB
                    **
```

```
                              **
00B3   9A                            CLI             CLEAR THE INTERRUPT MASK TO GET STARTED.
                              ***
00B4                                 RELATIVE        RELATIVE ADDRESSING MUST BE USED FOR THE
                              ***                    REMAINDER OF THE PROGRAM.
                              ***
                              ****************************************************************************
                              **
                              ** WAIT LOOP.  EXECUTES, UNTIL AN INTERRUPT OCCURS.
                              **
00B4   09 03 0B               PAUSE  BRCLR  FUNCT,PORTD,CHHYST WANT TO CHANGE HYST?
                              **                               YES...GO TO CHHYST.
00B7   06 03 04                      BRSET  SET,PORTD,SBIT     NO...'SET,PORTD' SET?
00BA   17 20                         BCLR   L_SET,STAT               NO...CLEAR 'L_SET,STAT'
00BC   20 F6                         BRA    PAUSE                      AND LOOP.
00BE   16 20                  SBIT   BSET   L_SET,STAT               YES...SET 'L_SET,STAT'
00C0   20 F2                         BRA    PAUSE                      AND LOOP.
                              **
                              ****************************************************************************
                              **
                              ** HYSTERESIS MODIFICATION ROUTINE.  PERMITS MODIFICATION OF THE
                              ** HYSTERESIS BUFFER WITHOUT REPROGRAMMING.
                              **                               YES...
00C2   A6 40                  CHHYST LDA    #BIT6              DISABLE TIMER INTERRUPT.
00C4   B7 09                         STA    TCR
                              ***
00C6   A6 08                         LDA    #%00001000         SAVE 'L_SET'
00C8   B4 20                         AND    STAT               INTO
00CA   B7 21                         STA    LSTAT              'LSTAT'.
00CC   A6 08                         LDA    #%00001000
00CE   B4 03                         AND    PORTD              'SET,PORTD' --> ACCUMULATOR
00D0   B1 21                         CMP    LSTAT              HAS THE SET SWITCH BEEN CHANGED?
00D2   27 15                         BEQ    DISPLA
                              ***                              YES...
00D4   A6 08                         LDA    #%00001000         --
00D6   B8 20                         EOR    STAT                 |-->CHANGE 'L_SET,STAT',
00D8   B7 20                         STA    STAT               --
00DA   3C 1E                         INC    HYST               THEN INCREMENT THE HYSTERESIS
00DC   3C 1C                         INC    HYSTPT             POINTER AND 'HYST'...
                              ***
00DE   B6 1C                         LDA    HYSTPT            --
00E0   A1 19                         CMP    #25                --
00E2   23 05                         BLS    DISPLA               --
                              ***                                  -- BUT NOT ABOVE 25.
00E4   4F                            CLRA                        --        THEN--->|
00E5   B7 1E                         STA    HYST                --               |
00E7   B7 1C                         STA    HYSTPT            --                 |
                              ***                                                |
00E9   A6 00                  DISPLA LDA    #%00000000         NO... JUST--------->|
00EB   B7 00                         STA    PORTA             --                 |
00ED   A6 C0                         LDA    #%11000000         --                |
00EF   B7 01                         STA    PORTB                --             \|/
                              ***                                   -- DISPLAY CURRENT 'HYST'.
00F1   BE 1C                         LDX    HYSTPT               --
00F3   D6 03 28                      LDA    TABLE,X            --
00F6   B7 02                         STA    PORTC             --
                              ***                              IS 'HYST' SETTING COMPLETE?
00F8   09 03 C7                      BRCLR  FUNCT,PORTD,CHHYST NO... KEEP CHECKING 'SET'.
00FB   04 20 04                      BRSET  NEGTIV,STAT,SIGN   YES... RESET THE DISPLAY.
00FE   1C 01                         BSET   POSTIV,PORTB
0100   20 02                         BRA    DIR
0102   1D 01                  SIGN   BCLR   POSTIV,PORTB
0104   08 20 05               DIR    BRSET  POSCT,STAT,SHOPOS
                              **
0107   CD 02 D8                      JSR    OUTCT
010A   20 03                         BRA    DUNCHG
```

```
                        ***
010C    CD 02 E5        SHOPOS  JSR     OUTPOS
                        ***
010F    0B 20 04        DUNCHG  BRCLR   FLASH,STAT,NO_INT  IF THE DISPLAY IS TO BLINK...
0112    A6 07                   LDA     #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
0114    B7 09                   STA     TCR                TIMER PRESCALER
0116    20 9C           NO_INT  BRA     PAUSE              PRIOR TO RETURNING.
                        ***
                        **
                        ***************************************************************************
                        ** MAXIMUM EXECUTION TIME FOR THE REMAINDER OF THE PROGRAM OCCURS
                        ** IF THE COUNTER ROTATES THROUGH ZERO AS THE DISPLAY MODE IS CHANGED
                        ** FROM THE BLINKING MODE TO THE COUNT MODE AT THE SAME TIME THAT THE
                        ** BLINKING ROUTINE IS CAUSING THE DISPLAY TO TOGGLE TO SHOW THE
                        ** POSITION IN DEGREES.
                        **     MAXIMUM EXECUTION TIME = 67 + 140 + 618 = 825 CLOCK CYCLES.
                        **
                        ***************************************************************************
                        **
                        **MODE CHANGE ROUTINE.  CHANGES THE DISPLAY MODE FROM
                        **       COUNT -> POSITION -> BLINKING -> COUNT ->....(ETC.)
                        **       MAXIMUM EXECUTION TIME OF 127 CLOCK CYCLES OCCURS WHEN THE
                        **       DISPLAY MODE IS CHANGED FROM DISPLAYING THE COUNT TO DISPLAYING
                        **       THE POSITION (IN DEGREES).
                        **       IF THE DISPLAY IS CHANGED FROM BLINKING TO A COUNT DISPLAY
                        **       EXECUTION TIME IS 67 CLOCK CYCLES.
                        **
0118    1F 0A           CHMODE  BCLR    B7,MR              AVOID REPEATED INTERRUPTS.
                        **
011A    0A 20 10                BRSET   FLASH,STAT,DIS_CT  IF FLASHING, DISPLAY COUNT...
011D    09 20 07                BRCLR   POSCT,STAT,DISPOS  IF SHOWING COUNT, DISPLAY POSITION...
0120    1A 20                   BSET    FLASH,STAT         ELSE, BLINK.
                        **
0122    A6 07                   LDA     #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
0124    B7 09                   STA     TCR                TIMER PRESCALER.
0126    80                      RTI
                        **
0127    18 20           DISPOS  BSET    POSCT,STAT      --
0129    CD 02 E5                JSR     OUTPOS           |-- DISPLAY CURRENT POSITION, AND WAIT.
012C    80                      RTI                     --
                        **
012D    A6 47           DIS_CT  LDA     #BIT6+BIT2+BIT1+BIT0  DISABLE TIMER INTERRUPT AND RESET
012F    B7 09                   STA     TCR                   TIMER PRESCALER.
0131    19 20                   BCLR    POSCT,STAT      --
0133    1B 20                   BCLR    FLASH,STAT        |
                        **                                |-- DISPLAY CURRENT COUNT, AND WAIT.
0135    CD 02 D8                JSR     OUTCT             |
0138    80                      RTI                     --
                        **
                        ***************************************************************************
                        **
                        ** BLINK ROUTINE.  INTERRUPT ROUTINE TO CHANGE THE DISPLAY FROM POSITION
                        **        TO COUNT OR VICE VERSA EVERY 31 ST TIMER INTERRUPT IF THE
                        **        'FLASH' BIT OF 'STAT' IS SET.
                        **        MAXIMUM EXECUTION TIME OF 140 CLOCK CYCLES OCCURS WHEN THE
                        **        DISPLAY IS TOGGLED FROM A COUNT DISPLAY TO A POSITION DISPLAY.
                        **
        0139            BLINK   EQU     $
0139    0F 09 DC                BRCLR   TIR,TCR,CHMODE        IF THE INTERRUPT WAS NOT A TIMER
                        **                                    INTERRUPT IT MUST BE FROM INT2.
                        **
013C    1F 09                   BCLR    TIR,TCR               AVOID REPEATED TIMER INTERRUPTS.
                        **
013E    3A 22                   DEC     TIMCT                 IF THERE HAVE BEEN 31 TIMER
0140    27 01                   BEQ     CHGDIS                INTERRUPTS  (1 SEC), IT'S TIME TO
                        **                                    CHANGE THE DISPLAY.
```

```
0142   80                 RTI                                   OTHERWISE, IT'S BACK TO WORK.
                   **
0143   A6 1F       CHGDIS LDA    #31                            RESET TIMCT TO 31 (1 SEC. INTERVAL).
0145   B7 22              STA    TIMCT
                   **
0147   B6 20              LDA    STAT                  --
0149   A8 10              EOR    #%00010000             |-- CHANGE 'POSCT' BIT OF 'STAT'.
014B   B7 20              STA    STAT                  --
                   **
014D   08 20 04           BRSET  POSCT,STAT,POSOUT      DECIDE ON CORRECT DISPLAY.
                   **
                   ************  CHANGE THE DISPLAY TO SHOW THE COUNT.....  ***************
                   **
0150   CD 02 D8           JSR    OUTCT
0153   80                 RTI
                   **
                   ************  OR HAVE THE DISPLAY SHOW THE POSITION.  *****************
                   **
0154   CD 02 E5    POSOUT JSR    OUTPOS
0157   80                 RTI
                   **
                   ***************************************************************************
                   **
                   **                         COUNT ROUTINE.
                   **       WHEN A COUNT IS RECEIVED THIS IS THE ENTRY POINT .
                   **       MAXIMUM EXECUTION TIME OF 618 CLOCK CYCLES OCCURS WHEN THE
                   **       COUNTER ROTATES CCW THROUGH ZERO AND THE POSITION (IN DEGREES)
                   **       IS BEING DISPLAYED.
                   **
                   **
                   ** CURRENT DIRECTION OF ROTATION IS DETERMINED BY INSPECTING THE STATUS
                   ** OF 'CH_A' AND 'CH_B'.  THE FOUR POSSIBILITIES AND THE ASSOCIATED
                   ** DIRECTION OF ROTATION ARE AS SHOWN BELOW.  NOTE THAT THIS SCHEME
                   ** PREVENTS MULTIPLE OSCILLATIONS ABOUT A SINGLE POINT FROM
                   ** REPEATEDLY INCREMENTING OR DECREMENTING THE COUNTER.
                   **
                   **   +--------+--------+-----------------+-----------------+
                   **   |  CH_A  |  CH_B  |   DIRECTION     | COUNT THE PULSE? |
                   **   |        |        |  OF ROTATION    |                 |
                   **   +--------+--------+-----------------+-----------------+
                   **   |   LO   |   LO   |      CW         |       NO        |
                   **   |   LO   |   HI   |      CCW        |       YES       |
                   **   |   HI   |   LO   |      CCW        |       NO        |
                   **   |   HI   |   HI   |      CW         |       YES       |
                   **   +--------+--------+-----------------+-----------------+
                   **
                   ********  FIRST SEE IF WE ARE SUPPOSED TO COUNT THIS INTERUPT.  ********
                   **
       0158        COUNT  EQU    $
0158   0A 03 01           BRSET  CH_B,PORTD,OKCT    IF CH_B IS LO WE DON'T COUNT THE
015B   80                 RTI                       INTERRUPT.
                   **
                   **************  IF THE INTERRUPT IS VALID UPDATE 'STAT'.  **************
                   **
015C   A6 7F       OKCT   LDA    #%01111111
015E   B4 20              AND    STAT               SAVE ALL OF THE OLD 'STAT' EXCEPT THE
0160   B7 20              STA    STAT               DIRECTION OF ROTATION.
0162   A6 80              LDA    #%10000000
0164   B4 03              AND    PORTD              'CH_A,PORTD' INDICATES THE DIRECTION
                   *                                OF ROTATION AND BECOMES 'UD,STAT'.
0166   BA 20              ORA    STAT               ADD THE RESULTS TO GET
0168   B7 20              STA    STAT               THE NEW 'STAT'.
                   **
                   ** DECIDE IF THE "SLACK" DUE TO BACKLASH/HYSTERESIS HAS BEEN TAKEN OUT.
                   **
016A   0E 20 09           BRSET  UD,STAT,HYSTCK  IF ROTATING CW SEE BELOW.
```

```
016D  B6 1F            LDA   HYSTCT         ELSE, SEE IF WE DECREMENT THIS TIME.
016F  27 4B            BEQ   CCW            IF HYSTCT=0, GO TO THE COUNT DOWN
                **                          ROUTINE.
0171  A0 01            SUB   #1             ELSE, DECREMENT THE HYSTERESIS COUNTER,
0173  B7 1F            STA   HYSTCT
0175  80               RTI                  AND WAIT FOR THE NEXT INTERRUPT.
                **
0176  B6 1E     HYSTCK LDA   HYST           IF ROTATING CW....
0178  B1 1F            CMP   HYSTCT         AND  HYST = HYSTCT ....
017A  27 03            BEQ   CW             COUNT THE PULSE .
017C  3C 1F            INC   HYSTCT         ELSE, INCREMENT THE HYSTERESIS COUNTER,
017E  80               RTI                  AND WAIT FOR ANOTHER PULSE.
                **
                **
                ****************************************************************************
                **
                **                     CLOCKWISE ROUTINE.
                **
      017F      CW     EQU   $
                **
                ***
                **************  INCREMENT THE BINARY COUNTER (BINCT).  *****************
                ***
017F  B6 11            LDA   LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
0181  AB 01            ADD   #1      LOBIN = LOBIN + 1 ; CARRY -> C,CCR
0183  B7 11            STA   LOBIN
                ***
0185  B6 10            LDA   HIBIN
0187  A9 00            ADC   #0             ADD THE CARRY TO THE HIGH BYTE.
0189  B7 10            STA   HIBIN
                ***
                ***
                ******************  CLR/SET MOD_32 APPROPRIATELY.  *********************
                ***
018B  B6 11            LDA   LOBIN        IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
018D  A4 1F            AND   #%00011111   NOT THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
018F  26 04            BNE   NOT_32
                ***
0191  1C 20            BSET  MOD_32,STAT
0193  20 02            BRA   DIRCHK
                ***
0195  1D 20     NOT_32 BCLR  MOD_32,STAT
                ***
                ***
0197  B6 10     DIRCHK LDA   HIBIN
0199  2B 19            BMI   CWNEG        IF HIBIN < 0 , WE'RE ROTATING CW TOWARD
                ***                       THE ORIGIN.
                ***
019B  26 10            BNE   CWPOS        ELSE IF BINCT .NE. 0 ,
019D  B6 11            LDA   LOBIN        WE'RE ROTATING CW
019F  26 0C            BNE   CWPOS        AWAY FROM THE ORIGIN.
                ***
01A1  15 20            BCLR  NEGTIV,STAT  ELSE, WE'VE GONE THROUGH ORIGIN IN CW
                ***                       DIRECTION.  CLR NEGATIVE SIGN.
01A3  AE 12            LDX   #PTR3   --
01A5  7F        CLRIT2 CLR   ,X         --
01A6  5C               INCX               --RESET ALL COUNTERS AND DEGRES TO ZERO.
01A7  A3 19            CPX   #THOUTH   --
01A9  23 FA            BLS   CLRIT2  --
01AB  20 4C            BRA   UPOUT        UPDATE OUTPUT.
                ***
01AD  AD 5E     CWPOS  BSR   ADDBCD
01AF  CD 02 32         JSR   INCPOS
01B2  20 45            BRA   UPOUT
                ***
01B4  CD 02 7A  CWNEG  JSR   SUBBCD
```

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01B7  CD 02 9A              JSR    DECPOS
01BA  20 3D                 BRA    UPOUT
                    ***
                    **
                    ************************************************************************
                    **
                    **                  COUNTER-CLOCKWISE ROUTINE.
                    **
      01BC          CCW     EQU    $
                    **
                    ***
                    ****************** CLR/SET MOD_32 APPROPRIATELY.  **********************
                    ***
01BC  B6 11                 LDA    LOBIN        IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
01BE  A4 1F                 AND    #%00011111   ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
01C0  26 04                 BNE    NO_32
                    ***
01C2  1C 20                 BSET   MOD_32,STAT
01C4  20 02                 BRA    DECBIN
                    ***
01C6  1D 20         NO_32   BCLR   MOD_32,STAT
                    ***
                    ***
                    *************** DECREMENT THE BINARY COUNTER (BINCT).  ****************
                    ***
01C8  B6 11         DECBIN  LDA    LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
01CA  A0 01                 SUB    #1      LOBIN = LOBIN - 1 ; BORROW -> C,CCR
01CC  B7 11                 STA    LOBIN
                    ***
01CE  B6 10                 LDA    HIBIN
01D0  A2 00                 SBC    #0      SUBTRACT THE CARRY FROM THE HIGH BYTE.
01D2  B7 10                 STA    HIBIN
                    ***
01D4  B6 10                 LDA    HIBIN
01D6  2A 1B                 BPL    CCWPOS        IF HIBIN .GE. 0 , WE'RE ROTATING CCW TOWARD
                    ***                          THE ORIGIN.
01D8  A1 FF                 CMP    #-1    --
01DA  26 10                 BNE    CCWNEG    --  ELSE IF BINCT .NE. -1 ,
01DC  B6 11                 LDA    LOBIN       --WE'RE ROTATING CCW AWAY
01DE  A1 FF                 CMP    #-1    --  FROM THE ORIGIN.
01E0  26 0A                 BNE    CCWNEG  --
01E2  14 20                 BSET   NEGTIV,STAT   ELSE, WE'VE GONE THROUGH ORIGIN IN CCW
                    ***                          DIRECTION.  SET NEGATIVE SIGN.
                    ***                          AND SET ALL COUNTERS APPROPRIATELY.
01E4  AE 12                 LDX    #PTR3   --
01E6  7F            CLREM   CLR    ,X        --
01E7  5C                    INCX               -- RESET ALL COUNTERS AND DEGRES TO ZERO.
01E8  A3 19                 CPX    #THOUTH   --
01EA  23 FA                 BLS    CLREM   --
                    ***
01EC  AD 1F         CCWNEG  BSR    ADDBCD
01EE  CD 02 32              JSR    INCPOS
01F1  20 06                 BRA    UPOUT
                    ***
01F3  CD 02 7A      CCWPOS  JSR    SUBBCD
01F6  CD 02 9A              JSR    DECPOS
                    ***
                    ***
                    **
                    ************************************************************************
                    **
                    ** OUTPUT ROUTINE. ROUTINE TO PRINT DATA TO THE OUTPUT PORTS.  BY
                    **       CALLING THE APPROPRIATE SUBROUTINE.('OUTCT' TO OUTPUT THE
                    **       THE COUNT AND 'OUTPOS' TO OUTPUT THE POSITION).
                    **
      01F9          UPOUT   EQU    $
```

```
                            **
01F9  04 20 04                      BRSET   NEGTIV,STAT,MINUS  --
01FC  1C 01                         BSET    POSTIV,PORTB         --
01FE  20 02                         BRA     DISCHK                 --
                            **                                   --    SET THE NEGATIVE SIGN
0200  1D 01                 MINUS   BCLR    POSTIV,PORTB       --      APPROPRIATELY.
                            **
0202  09 20 04              DISCHK  BRCLR   POSCT,STAT,PUTCT
                            **
0205  CD 02 E5                      JSR     OUTPOS
0208  80                            RTI
                            **
0209  CD 02 D8              PUTCT   JSR     OUTCT
020C  80                            RTI
                            **
                            ***************************************************************************
                            ***********  SUBROUTINE TO INCREMENT THE BCD COUNTER (BCDCT).  *********
                            ***
020D  B6 16                 ADDBCD  LDA     CTPTR1
020F  AB 01                         ADD     #1
0211  A1 63                         CMP     #99     CTPTR > 99 ?
0213  23 05                         BLS     OK1     NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
0215  A0 64                         SUB     #100    YES... MODIFY THE CTPTR,
0217  99                            SEC             SET THE CARRY, AND
0218  20 01                         BRA     OK1A    USE TABLE LOOK UP.
                            ***
021A  98                    OK1     CLC                     NO CARRY EXISTS IF WE ENTER AT THIS POINT.
021B  B7 16                 OK1A    STA     CTPTR1  --
021D  97                            TAX                --
                            ***                          -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
021E  D6 03 28                      LDA     TABLE,X  --
0221  B7 1B                         STA     TENONE  --
0223  24 0C                         BCC     NOMO            AND CONTINUE ONLY IF THERE WAS A CARRY.
                            ***
                            ***
0225  B6 15                         LDA     CTPTR2
0227  A9 00                         ADC     #0      ADD THE CARRY.
0229  B7 15                         STA     CTPTR2  --
022B  97                            TAX                --
                            ***                          -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
022C  D6 03 28                      LDA     TABLE,X  --
022F  B7 1A                         STA     HUNDRD  --
                            ***
0231  81                    NOMO    RTS
                            ***
                            ***************************************************************************
                            *******  SUBROUTINE TO INCREMENT THE POSITION COUNTER (DEGRES).  *******
                            ***
                            ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                            ****     NUMBER.
                            ****
0232  0D 20 04              INCPOS  BRCLR   MOD_32,STAT,INC7   'MOD_32,STAT' SET ?
                            ****
0235  A6 08                         LDA     #8                    YES ...
0237  20 02                         BRA     INC             INCREMENT THE POSITION BY 0.008 DEGREES.
                            ****
0239  A6 07                 INC7    LDA     #7                    NO ....
023B  B7 1D                 INC     STA     POSINC          INCREMENT THE POSITION BY 0.007 DEGREES.
                            ****
                            **** ROUTINE TO INCREMENT THE POSITION COUNTER ,'DEGREES',BY A
                            ****     PREDETERMINED AMOUNT, 'POSINC'.
                            ****
023D  B6 14                         LDA     PTR1
023F  BB 1D                         ADD     POSINC
0241  A1 09                         CMP     #9      PTR1 > 9 ?
0243  23 05                         BLS     OK3     NO, WE'RE OK HERE.  LOOK UP THE FIRST DIGIT.
```

```
0245   A0 0A                   SUB    #10     YES... MODIFY THE CTPTR,
0247   99                      SEC            SET THE CARRY, AND
0248   20 01                   BRA    OK3A    USE TABLE LOOK UP.
                       ****
024A   98              OK3     CLC                  NO CARRY EXISTS IF WE ENTER AT THIS POINT.
024B   B7 14           OK3A    STA    PTR1    --
024D   97                      TAX              --
                       ****                       -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
024E   D6 03 28                LDA    TABLE,X  --
0251   B7 19                   STA    THOUTH  --
0253   24 24                   BCC    DONE            AND CONTINUE ONLY IF THERE WAS A CARRY.
                       ****
                       ****
0255   B6 13                   LDA    PTR2
0257   A9 00                   ADC    #0      ADD THE CARRY.
0259   A1 63                   CMP    #99     PTR2 > 99 ?
025B   23 05                   BLS    OK4     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
025D   A0 64                   SUB    #100    YES...MODIFY THE CTPTR,
025F   99                      SEC            SET THE CARRY,
0260   20 01                   BRA    OK4A    AND USE TABLE LOOK UP.
                       ****
0262   98              OK4     CLC                  NO CARRY EXISTS IF WE ENTER AT THIS POINT.
0263   B7 13           OK4A    STA    PTR2    --
0265   97                      TAX              --
                       ****                        -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0266   D6 03 28                LDA    TABLE,X  --
0269   B7 18                   STA    HUNDTH  --
026B   24 0C                   BCC    DONE            AND CONTINUE ONLY IF THERE WAS A CARRY.
                       ****
                       ****
026D   B6 12                   LDA    PTR3
026F   A9 00                   ADC    #0      ADD THE CARRY.
0271   B7 12                   STA    PTR3    --
0273   97                      TAX              --
                       ****                       -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0274   D6 03 28                LDA    TABLE,X  --
0277   B7 17                   STA    ONEDEG  --
                       ****
0279   81              DONE    RTS
                       ***
                       **
                       ****************************************************************************
                       ********  SUBROUTINE TO DECREMENT THE BCD COUNTER (BCDCT).  ************
                       ***
027A   B6 16           SUBBCD  LDA    CTPTR1
027C   A0 01                   SUB    #1      CTPTR > 99 ?
027E   24 03                   BCC    OK6     NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
0280   AB 64                   ADD    #100    YES, MODIFY THE CTPTR, AND
0282   99                      SEC            GENERATE A BORROW.
                       ***
0283   B7 16           OK6     STA    CTPTR1  --
0285   97                      TAX              --
                       ***                        -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
0286   D6 03 28                LDA    TABLE,X  --
0289   B7 1B                   STA    TENONE  --
028B   24 0C                   BCC    COMPLT        AND CONTINUE ONLY IF THERE WAS A BORROW.
                       ***
                       ***
028D   B6 15                   LDA    CTPTR2
028F   A2 00                   SBC    #0      SUBTRACT THE CARRY. CTPTR > 99 ?
0291   B7 15                   STA    CTPTR2  --
0293   97                      TAX              --
                       ***                         -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0294   D6 03 28                LDA    TABLE,X  --
0297   B7 1A                   STA    HUNDRD  --
                       ***
```

```
0299   81            COMPLT  RTS
                     ***
                     ****************************************************************************
                     *******  SUBROUTINE TO DECREMENT THE POSITION COUNTER (DEGRES).  *******
                     ***
                     ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                     ****     NUMBER.
                     ****
029A   0D 20 04      DECPOS  BRCLR   MOD_32,STAT,DEC7        'MOD_32,STAT' SET ?
                     ****
029D   A6 08                 LDA     #8                      YES...
029F   20 02                 BRA     DEC           DECREMENT THE POSITION BY 0.008 DEGREES.
                     ****
02A1   A6 07         DEC7    LDA     #7                      NO ....
02A3   B7 1D         DEC     STA     POSINC        DECREMENT THE POSITION BY 0.007 DEGREES.
                     ****
                     **** ROUTINE TO DECREMENT THE POSITION COUNTER ,'DEGREES',BY A
                     ****     PREDETERMINED AMOUNT, 'POSINC'.
                     ****
02A5   B6 14                 LDA     PTR1
02A7   B0 1D                 SUB     POSINC  PTR1 < 0 ?
02A9   24 03                 BCC     OK8     NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.
02AB   AB 0A                 ADD     #10     YES, MODIFY THE CTPTR, AND
02AD   99                    SEC             GENERATE A BORROW.
                     ****
02AE   B7 14         OK8     STA     PTR1    --
02B0   97                    TAX               --
                     ****                        -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
02B1   D6 03 28              LDA     TABLE,X   --
02B4   B7 19                 STA     THOUTH  --
02B6   24 1F                 BCC     DUNSUB        AND CONTINUE ONLY IF THERE WAS A BORROW.
                     ***
                     ***
02B8   B6 13                 LDA     PTR2
02BA   A2 00                 SBC     #0      SUBTRACT THE BORROW.  PTR2 < 0 ?
02BC   24 03                 BCC     OK9     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
02BE   AB 64                 ADD     #100    YES, MODIFY THE CTPTR, AND
02C0   99                    SEC             GENERATE A BORROW.
                     ***
02C1   B7 13         OK9     STA     PTR2    --
02C3   97                    TAX               --
                     ***                         -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02C4   D6 03 28              LDA     TABLE,X   --
02C7   B7 18                 STA     HUNDTH  --
02C9   24 0C                 BCC     DUNSUB        AND CONTINUE ONLY IF THERE WAS A CARRY.
                     ***
                     ***
02CB   B6 12                 LDA     PTR3
02CD   A2 00                 SBC     #0      SUBTRACT THE BORROW.
02CF   B7 12                 STA     PTR3    --
02D1   97                    TAX               --
                     ****                        -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02D2   D6 03 28              LDA     TABLE,X   --
02D5   B7 17                 STA     ONEDEG  --
                     ****
02D7   81            DUNSUB  RTS
                     ***
                     **
                     **
                     ****************************************************************************
                     **
                     ** OUTPUT COUNT (OUTCT).  SUBROUTINE TO MOVE THE CURRENT COUNT (BCDCT)
                     **       TO THE OUTPUT PORTS.  REMOVES THE DECIMAL POINT FROM THE
                     **       DISPLAY AND BLANKS ALL BUT THE LEAST SIGNIFICANT DIGIT. ALSO
                     **       SETS THE MINUS SIGN IF APPROPRIATE.
                     **
```

```
          02D8                  OUTCT   EQU     $
                                **
02D8      B6 1B                         LDA     TENONE
02DA      B7 02                         STA     PORTC
                                **
02DC      B6 1A                         LDA     HUNDRD
02DE      B7 00                         STA     PORTA
                                **
02E0      1E 01                         BSET    DECPT,PORTB
02E2      19 01                         BCLR    BLANK,PORTB
                                **
02E4      81                            RTS
                                **
                                ***************************************************************************
                                **
                                ** OUTPUT POSITION (OUTPOS).  SUBROUTINE TO MOVE THE CURRENT POSITION
                                **       COUNT (BCDCT) TO THE OUTPUT PORTS.  THE DECIMAL POINT IS
                                **       DISPLAYED , AND ONLY THE MOST SIGNIFICANT DIGIT IS BLANKED.
                                **
          02E5                  OUTPOS  EQU     $
                                **
02E5      B6 19                         LDA     THOUTH  --
02E7      A1 05                         CMP     #5         --
02E9      25 2D                         BLO     TRUNC      --    IF 5 > 'THOUTH' SIMPLY TRUNCATE THE
02EB      B6 18                         LDA     HUNDTH        -- DISPLAY.  OTHERWISE...
02ED      A4 09                         AND     #9            -- IF THE LAST DIGIT ISN'T A NINE IT IS
02EF      A1 09                         CMP     #9            -- EASY TO ROUND UP.  JUST ADD A ONE.
02F1      26 1D                         BNE     DECIMAL       --
02F3      B6 18                         LDA     HUNDTH        -- BUT IF THE LAST DIGIT IS A NINE CHECK TO
02F5      A1 99                         CMP     #$99          -- SEE IF IT'S 99.  IF SO IT GETS GRIM.
02F7      27 04                         BEQ     UGLY          --
02F9      AB 07                         ADD     #7            -- IF THE NUMBER IS X9 AND X .NE. 9, THEN
02FB      20 1D                         BRA     PCOUT         -- JUST ADD SEVEN TO ROUND UP. DUE TO
                                **                            -- HEXIDECIMAL.
                                **                            -- IF THE LOW TWO DIGITS ARE BOTH NINES
02FD      A6 00                 UGLY    LDA     #00        --    AND WE NEED TO ROUND UP....
02FF      B7 02                         STA     PORTC    --      MAKE THE LOW TWO DIGITS BOTH ZEROS
0301      99                            SEC           --         AND SET THE CARRY.
                                **
0302      B6 17                         LDA     ONEDEG  --       CHECK THE LAST DIGIT AS BEFORE.
0304      A4 09                         AND     #9         --    IF USING THIS PORTION OF THE CODE
0306      A1 09                         CMP     #9         --    THERE HAD TO BE A CARRY.
0308      26 13                         BNE     NEXT          -- IF THE LAST DIGIT IS A NINE DO THE
030A      B6 17                         LDA     ONEDEG       --  CARRY HERE.  IF NOT USE THE ADC
030C      AB 07                         ADD     #7          --   INSTRUCTION TO TAKE CARE OF IT
030E      20 11                         BRA     PAOUT    --      BELOW.
0310      B6 18                 DECIMAL LDA     HUNDTH --
0312      AB 01                         ADD     #1          --
                                **                           --  THIS IS ALL THAT NEEDS TO BE DONE IF
0314      B7 02                         STA     PORTC     --     THE LAST DIGIT IS NOT A NINE.
0316      20 05                         BRA     NEXT   --
                                **
0318      B6 18                 TRUNC   LDA     HUNDTH --
031A      B7 02                 PCOUT   STA     PORTC     --  AND IF THERE IS NO CARRY IT'S EVEN EASIER.
031C      98                            CLC            --
                                **
031D      B6 17                 NEXT    LDA     ONEDEG
031F      A9 00                         ADC     #0
0321      B7 00                 PAOUT   STA     PORTA
                                **
0323      18 01                         BSET    BLANK,PORTB
0325      1F 01                         BCLR    DECPT,PORTB
                                **
0327      81                            RTS
                                **
                                ***************************************************************************
```

```
                          **
                          ** SET UP THE TABLE TO BE USED WITH BCD INCREMENT/DECREMENT ROUTINES.
                          **
                          *       ENDS
                          *       DATA
0328   00 01 02 03 04     TABLE   FCB     $00,$01,$02,$03,$04,$05,$06,$07,$08,$09
032D   05 06 07 08 09
0332   10 11 12 13 14             FCB     $10,$11,$12,$13,$14,$15,$16,$17,$18,$19
0337   15 16 17 18 19
033C   20 21 22 23 24             FCB     $20,$21,$22,$23,$24,$25,$26,$27,$28,$29
0341   25 26 27 28 29
0346   30 31 32 33 34             FCB     $30,$31,$32,$33,$34,$35,$36,$37,$38,$39
034B   35 36 37 38 39
0350   40 41 42 43 44             FCB     $40,$41,$42,$43,$44,$45,$46,$47,$48,$49
0355   45 46 47 48 49
035A   50 51 52 53 54             FCB     $50,$51,$52,$53,$54,$55,$56,$57,$58,$59
035F   55 56 57 58 59
0364   60 61 62 63 64             FCB     $60,$61,$62,$63,$64,$65,$66,$67,$68,$69
0369   65 66 67 68 69
036E   70 71 72 73 74             FCB     $70,$71,$72,$73,$74,$75,$76,$77,$78,$79
0373   75 76 77 78 79
0378   80 81 82 83 84             FCB     $80,$81,$82,$83,$84,$85,$86,$87,$88,$89
037D   85 86 87 88 89
0382   90 91 92 93 94             FCB     $90,$91,$92,$93,$94,$95,$96,$97,$98,$99
0387   95 96 97 98 99
                          *       ENDS
                          *       CODE
                          ****************************************************************************
                          **
                          **                        SET UP MASK OPTION REGISTER.
                          **
038C                              ABSOLUTE          JUST TO ENSURE THAT THE INTERRUPT VECTORS
                          **                        ARE CORECTLY LOCATED.
                          **
                          **
0F38                              ORG     MOR
0F38   07                         FCB     #BIT2+BIT1+BIT0
                          **
                          **      COMMENTS:
                          **      BIT 7   CLOCK SOURCE  0 = CRYSTAL.
                          **      BIT 6   TIMER OPTION  0 = INTERNAL.
                          **      BIT 5   TIMER/CLOCK SOURCE  0 = INTERNAL.
                          **      BIT 4   NOT USED.
                          **      BIT 3   NOT USED.
                          **      BIT 2   SET  -
                          **      BIT 1   SET    -  PRESCALE SELECT  111 => 128
                          **      BIT 0   SET  -
                          **
                          **
                          ****************************************************************************
                          **
                          **                         ASSIGN INTERRUPT VECTORS.
                          **
0FF8                              ORG     INTRPT
                          **
0FF8   0139                       FDB     BLINK   TIMER/INT2 INTERRUPT VECTOR.
0FFA   0158                       FDB     COUNT   EXTERNAL INTERRUPT VECTOR.
0FFC   0158                       FDB     COUNT   SOFTWARE INTERRUPT VECTOR, NOT USED.
0FFE   0080                       FDB     RESTRT  RESET VECTOR.
                          **
                          **
                          **
                                  ENDS
1000                              END

     Lines Assembled :  973            Assembly Errors :  0
```

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